Durability of Reinforced Concrete Beams Repaired with Various Repair Materials

by

Hamoud Ahmad Farhan Dehwah

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
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In

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This thesis, written by **HAMOUD AHMAD FARHAN DEHWAH** under the direction of his thesis committee, and approved by all the members, has been presented to and accepted by the Dean, College of Graduate Studies, in partial fulfillment of the requirements for the degree of

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1963 ١٣٨٣
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الله

بسم الله الرحمن الرحيم

وما أوتيتم من العلم إلا قليلا

صدق الله العظيم

DEDICATED

TO MY BELOVED PARENTS, BROTHERS, WIFE AND CHILDREN

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All praise, thanks and gratitude first and last be to Almighty Allah, who provided the human being the basic-tools for education, and learning. Without these tools which are hearing, sight, intelligence and affections no one can achieve any knowledge. *(It is He who brought you forth from the wombs of your mothers when Ye knew nothing and He gave you hearing and sight and intelligence and affections that Ye may give thanks)* Nahl-78.

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THESIS ABSTRACT

Name : ***Hamoud Ahmad Farhan Dehwah***

Title of Study : ***Durability of Reinforced Concrete Beams Repaired With Various Repair Materials***

Major Field : ***Civil Engineering (Structures)***

Deterioration of concrete structures is a serious problem in the countries along the Arabian Gulf. Various repair techniques and materials are developed and used successfully in the western countries which have a temperate climate. The aggressive environmental conditions of the Arabian Gulf countries which are completely different from the Western conditions necessitate retesting and re-evaluation of these repair materials and techniques.

Renovation and repair work will be a major challenge to the maintenance engineers in this area. Before any repair/renovation work is undertaken it is necessary that the repair materials be tested for their performance and suitability. This study was carried out to evaluate the performance of a few repair materials in resisting rebar corrosion. The experimental work was carried out in three stages. In the first stage, the repair materials were evaluated by conducting water permeability, chloride permeability and accelerated corrosion tests. In the second stage, these repair materials were used to repair reinforced concrete beams and they were exposed to sodium chloride solution. The resistance to corrosion was evaluated by measuring

half-cell potentials and corrosion rates of rebars using Tafel Plot technique. In the third stage, the effect of heat-cool cycling on the corrosion resistance performance of the repair materials and repaired beams was undertaken.

The water permeability of all the repair materials, viz. silica fume mortar, polymer modified cementitious mortar, ordinary cement mortar and ferrocement mortar was lower than that of plain concrete. The chloride permeability of silica fume mortar and polymer modified cement mortar samples was lower than that of plain concrete samples. Ordinary cement mortar samples, however exhibited higher chloride permeability. The time for initiation of corrosion, i.e. breakdown of passivity was longer in silica fume mortar and polymer modified cementitious mortar samples compared with plain concrete samples. The time for initiation of corrosion was smaller in ferrocement and ordinary cement mortar samples compared to plain concrete samples. This indicates that structural components exposed to chloride ions and stray currents, or brackish water should not be repaired using ordinary cement mortar and ferrocement mortar.

The half-cell potentials and corrosion rates of rebars in repaired beams were lower than those in plain concrete beams. The half-cell potentials and corrosion rates of rebars in beams subjected to heat-cool cycling were higher than those in beams which were not subjected to heat-cool cycling. This indicates that thermal cycling accelerates the corrosion process.

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عنوان الدراسة	:	قوة تحمل كمرات الخرسانة المسلحة المصلحة بمواد اصلاح مختلفة
التـخـصص	:	هندسة مدنية (إنشاءات)
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التدهور في الإنشاءات الخرسانية يمثل مشكلة خطيرة خاصة في الدول المطلة على الخليج العربي . وقد تطورت مواد الإصلاح وتقنياته واستعملت بنجاح في الدول الغربية ذات المناخ المعتدل . إن الظروف والأحوال البيئية لدول الخليج العربي والتي تختلف إختلافا كليا عن الأحوال والظروف الغربية تستلزم إختبار وتقييم مواد الإصلاح وتقنياته .

التجديد وعمل الإصلاح سيكون مجالا صعبا ومتحديا لمهندسي صيانة الإنشاءات . وقبل مباشرة أي عمل اصلاح أو تجديد يجب أن تختبر وتفحص مواد الإصلاح لتجديد أدائها وملائمتها . وقد عملت هذه الدراسة لتقييم أداء عدد من مواد الإصلاح الشائعة الاستخدام في مقاومة صدأ حديد التسليح في الخرسانة المسلحة . ونفذت التجارب المعملية على ثلاث مراحل في المرحلة الأولى قيمت مواد الإصلاح بواسطة نفاذية المياه والكلورايد واختبارات الصدأ المعجلة . وفي المرحلة الثانية أستعملت مواد الإصلاح هذه لإصلاح كمرات خرسانية مسلحة وغمرت جزئيا بمحلول ملح كلوريد الصوديوم . وقيمت مقاومة الصدأ بواسطة جهد بطارية نصفية وتسارع الصدأ بواسطة قانون تفل . وفي المرحلة الثالثة أخذ في الإعتبار تأثير دورات التسخين والتبريد على اداء مقاومة الصدأ في مواد الإصلاح .

وقد بينت النتائج أن نفاذية الماء في كل مواد الإصلاح مثل ملاط ابخرة السيليكا وملاط البوليمر الإسمنتى المعدل وملاط الإسمنت العادي وملاط الإسمنت الحديدي كانت أقل من نفاذية الماء في الخرسانةالعادية . ونفاذية الكلورايد في عينات ملاط ابخرة السيليكا وملاط البوليمر الإسمنتي المعدل كانت أقل من نفاذية الكلورايد في عينات الخرسانة العادية . أما عينات ملاط الإسمنت العادي فقد بينت نفاذية إعلى للكلورايد . والوقت الأولى للصدأ كان أطول في عينات ملاط أبخرة السيليكا وملاط البوليمر الإسمنتي المعدل مقارنة بعينات الخرسانة العادية . وهذا يوضح أن أجزاء المنشآت التي تتعرض لأيونات الكلورايد وتيارات كهربائية أو مياه مالحة يجب تجنب اصلاحها بإستخدام ملاط الإسمنت العادي وملاط الإسمنت الحديدي قدر الإمكان .

أيضا بينت النتائج أن جهد البطارية النصفية وتسارع الصدأ كان أقل في الكمرات المصلحة عنها في الكمرات الأساسية . وجهد البطارية النصفية وتسارع الصدأ في حديد الكمرات التي عرضت الى دورات تسخين وتبريد كانت أعلى من تلك التي لم تعرض لدورات تسخين وتبريد . وهذا يبين ان الدورة الحرارية تسارع بعملية الصدأ .

درجة الماجستير في علوم الهندسة المدنية
جامعة الملك فهد للبترول والمعادن
الظهران – المملكة العربية السعودية
يناير ١٩٩٠م

CHAPTER 1

INTRODUCTION

1.1 Deterioration of Concrete in the Arabian Gulf Region

Deterioration of reinforced concrete structures is a serious problem in many countries especially those on the Arabian Gulf seaboard. Reinforced concrete is a highly durable material if it is manufactured properly, but reinforced concrete structures in these countries deteriorate more rapidly than in most other areas of the world. They show earlier signs of distress and alarming degree of deterioration within a short time period of 10 to 15 years. The factors contributing to deterioration of concrete structures in these regions include, severe climatic conditions, aggressive environmental conditions and marginal aggregates. The use of unsuitable specifications and designs, use of unskilled labour which lead to poor construction practices, use of unsuitable materials and equipment are other factors which contributed to the deterioration process. Quick implementation of projects and the unprecedented rate of construction have not allowed development of design and construction specifications suitable for local conditions. In the last two decades particularly since 1972, the Arabian Gulf countries have experienced a more rapid increase in the construction expenditure than any other area in the world, and this has put a great strain on the quality control of construction industry. The absence of close supervision, quality control assurance, lack of specifications suitable for local conditions, and awareness of the problem in the people during construction time are also other factors which have accelerated the deterioration process and magnified the problem. According to previous studies [2,3] the main causes of deterioration of concrete structures in this region in decreasing order are, corrosion of reinforcement, sulfate attack, salt weathering and cracking due to environmental effects and potential aggregate-cement reactivity. These factors interact with each other to aggravate the deterioration processes [1-9].

Since the number of structures suffering from rebar corrosion is far more than those due to other phenomena, a brief discussion on mechanisms of corrosion of rebars is discussed in the following paragraphs.

1.2 Corrosion of Reinforcement

Corrosion is defined as the reaction of a metal with its environment and it can occur by dry or wet reaction [19].

Deterioration of concrete due to corrosion of steel reinforcement has received increasing attention in recent years and became the international topic of the hour and a topic of discussion among concrete technologists and corrosion scientists, particularly in Saudi Arabia and the other Arabian Gulf countries because of the pre-mature deterioration of structures in this region. Extensive research is in progress in this region to enhance the Service life of concrete structures.

1.2.1 Factors Influencing Corrosion

Concrete normally provides an ideal environment for protecting reinforcing steel from corrosion. The high alkalinity of pore solution (PH > 11) causes the formation of a thin invisible protective oxide film on the steel reinforcement, which prevents it from corrosion. Corrosion is initiated once this protective layer is destroyed. The protective layer is destroyed by aggressive species like chlorides. Chloride ions are considered the major cause of corrosion of steel reinforcement. Carbonation, cracking, and mechanical failure of the cover are other causes of corrosion. The rate of corrosion of steel reinforcement is strongly influenced by the environmental factors and the properties of concrete. The low permeability of concrete minimizes penetration of water and air which are essential for corrosion mechanism to sustain. Type of cement, admixtures, water cement ratio, construction practices, cracks and concrete cover, are also other factors which control the initiation and propagation of the corrosion process.

1.2.2 Mechanisms of Corrosion

For the corrosion to take place a composite of anodes and cathodes electrically connected through the body of steel itself are required.

At the anode, Iron is oxidized to ferrous ions:

$$Fe = Fe^{++} + 2e^{-} \ldots\ldots\ldots\ldots (i)$$

At the cathode in the presence of oxygen and moisture the reaction

$$H_2O + 1/2\, O_2 + 2e^{-} = 2(OH) \ldots\ldots (ii)$$

will proceed the final reaction which results in the formation of rust is shown by reaction (iii).

$$Fe^{++} + 2(OH) = Fe(OH)_2 \ldots\ldots\ldots\ldots (iii)$$

The products of corrosion (rust) occupy a greater volume than the steel itself. The increased volume exerts substantial stresses on the surrounding concrete. Since concrete is weak in tension, it cracks because of corrosion of rebar.

1.3 Prevention of Deterioration

Deterioration of concrete can be minimized by using proper mix design techniques and proper materials and proper placement techniques. Concrete mixes have to be designed for the service environment. Since all the deterioration phenomena are permeability related, importance should be paid to the production of dense and impermeable concrete.

Permeability is the property of a material that governs the rate of flow of a fluid into a porous solid. The permeability of material to water usually determines the rate of deterioration, The higher the permeability, the faster the deterioration. Actually permeability is considered the key of concrete deterioration. There are different factors controlling permeability of concrete. Since strength and permeability are related to each other through the capillary porosity, as a first approximation the factors that influence strength of concrete also influence its permeability. A reduction in the volume of large capillary voids in the paste matrix would reduce the permeability. This should be possible by using a low water cement ratio, adequate cement content and proper compaction and curing conditions. Similarly, proper attention to aggregate size and grading, thermal and shrinkage strains, and avoiding premature or excessive loading are necessary steps to reduce the incidence of microcracking in the transition zone which appears to be a major cause of high permeability of concrete in practice. [11].

Studies have been carried out at the King Fahd University of Petroleum and Minerals to investigate the mix design parameters and materials that should be used for the production of dense and impermeable concrete. The mix design parameters investigated included binary aggregate, proportioning, water cement ratio and cement factor. The effect of using mineral and chemical admixtures to produce durable concrete was also investigated. These investigations have culminated in a wealth of useful data which can be used in the construction of new structures. However, much work is needed towards identifying materials and techniques for repair and restoration of the existing deteriorating structures. [1,11].

1.4 Scope and objectives of the study

The repair and maintenance of concrete structures in Saudi Arabia and the other Arabian Gulf Countries are major challenge to the civil engineers. The need for repair and maintenance stems from lack of durability and serviceability, in addition to alarming degree of deterioration in the concrete structures; and it also stems from the fact that it is too difficult to replace buildings, dams, bridges, highways and other structures by new structures, because of time factor and high cost. In general, constraints on the economy of the Arabian Gulf Countries have put a tremendous pressure on the engineers to select appropriate repair materials and techniques which are durable in these harsh environmental conditions and can protect the repaired concrete structures.

Numerous repair materials and techniques are presently in use. These repair materials and techniques have been used successfully in the United State of America and other countries with temperate climatic conditions for which they have been developed. Several manufacturers of these repair materials claim success based on western experience. But it is essential that the performance of these materials must be tested for the environmental conditions of the Arabian Gulf Countries. This investigation was carried out to evaluate the durability performance of repair materials using conventional techniques. Water permeability, chloride permeability and impressed current tests were conducted on specimens made of these repair materials. The durablity performance of reinforced concrete beams repaired with several repair materials were performed. Some repaired beams were exposed to heat-cool cycling and then to chloride solution. The other repaired beams exposed to chloride solution only. The corrosion of rebars for all beams was monitored using electrochemical techniques such as, half-cell potential, corrosion rate measurement and potential noise measurement. The effect of heat-cool cycling on the corrosion of rebars in the repaired beams and repair materials was also investigated.

The main objective of this research was to investigate the durability performance of reinforced concrete beams repaired by various repair materials. The following repair materials were investigated.

(1) Conventional cementitious mortar;

(2) Ferro-cement mortar;

(3) Polymer modified cementitious mortar;

(4) Silica fume mortar

The specific objectives of the investigation are:

(1) to evaluate the chloride permeability and water Permeability of the repair materials.

(2) to evaluate the corrosion of rebars imbedded in these repair materials.

(3) to study the corrosion behavior of reinforced concrete beams repaired with various repair materials.

(4) to study the effect of heat-cool cycling on the repaired beams and repair materials.

(5) to evaluate and compare the effectiveness of these repair materials.

CHAPTER 2

CONCRETE REPAIR MATERIALS AND TECHNIQUES

2.1 Need for Repair

In general deteriorating concrete structures need to be repaired in order to maintain safety and appearance and to extend their service life. In particular the purposes of repair are, to improve the functional performance of the structure, restore and increase the strength and stiffenss, improve appearance of the concrete surface, provide water-tightness, prevent access of corrosive materials to reinforcement and improve the durability performance of the structure The proper repair of deteriorated concrete structures depends on the precise diagnosis and evaluation of the causes of deterioration. Consequently, the first step in a successful repair program is to carry out a systematic field investigation to diagnose and evaluate the causes and factors contributing to the deterioration. Secondly, based on the conclusion of the careful evaluation of causes, diagnosis, extent and consequences of deterioration the repair techniques, repair procedures, and repair materials can be selected considering economy, compatiblity and efficiency of repair. It must be remembered that defects are often due to a combination of causes. Nothing will be gained by carrying out a repair if the fault is likely to reoccur almost immediately . This point is often forgotten, but its importance cannot be overstated. [5,6,9,12,23,27,28].

Cost, ease of application and efficiency are the major considerations in choosing the repair materials and repair techniques. Some repair materials are very expensive, some are fair and some are cheap. Similarly, some repair techniques require expensive equipments and skilled labour for placement and some do not. It is the responsibility of the engineers to seek and utilize the most efficient and economical repair methods. [5,6,9,12,23,27,28].

2.2 Classifications of Repair Materials

Basically repair materials are classified into different types, such as cementitious materials, epoxy-resins, polyster-resins, polymer-latex and polyvinyl acetate. Cementitious materials and epoxy-resins are the most widely used nowadays. The cementitious materials are considered effective and economical repair materials in most of the cases [23,27,28].

2.2.1 Cementitious Materials

A Cementitious material consists mainly of cement and may be impregnated by polymer, silica-fume, fly-ash or any other material. Ordinary or rapid hardening portland cement is the cheapest basic material for use in the repair of concrete structures. Also, sulphate-resisting portland cement may occasionally be necessary for areas which are in contact with sulphate bearing soils. Cementitious materials have proved to be the most cost effective. In addition to their cost advantages, cement-based repair materials have mechanical properties that are essentially similar to those of the concrete that is being repaired, so the possibility of using them should normally be considered before deciding on use of any other repair materials [27].

Conventional Cement Mortar

Conventional cement mortars have been used in the past as repair materials. The correctly designed sand cement ratio and water cement ratio mixes often incorporating special water proofing admixtures based on quality of sands carefully placed by skilled operatives are the most cost effective repair materials where the cover of the reinforcement exceeds 25-30 mm. Many concrete repairs carried out with carefully applied sand cement mortars in the 1930s are still around today [23]. This type of repair needs a careful and proper application such as:

(1) Proper cleaning: The concrete surfaces to be repaired must be clean, sound, and free from oil and grease. All loose materials and cement-laitance should be removed by sandblasting or high pressure water jet or high air pressure. Reinforcement bars must be derusted by wire brushing or sandblasting. [23,29].

(2) Obtaining a good bond between the new mortar and the old

concrete. This can be achieved by using synthetic bonding agents or epoxy-based adhesive depending on the purpose of repair, strength of the bond and chemical resistance, for example, if the area to be repaired will be subjected to heavy traffic or impact loading the epoxy-resins should be considered.

(3) Elimination or reduction of shrinkage.

(4) Proper construction methods (proper compaction and proper curing conditions).

Ferrocement Mortar

According to ACI Committee 549 [33] ferrocement is defined as follows:

"Ferrocement is a type of thin wall reinforced concrete construction, where usually a hydraulic cement is reinforced with layers of continuous and relatively small diameter mesh. Mesh may be made of metalic materials or other suitable materials".

Ferrocement has been used as a construction material for several decades for different applications in many countries, especially in the developing countries and Europe. Jean Louis Lambot pioneered the use ferrocement in France. He constructed a concrete rowing boat in which inter locking wires and thin bars were used as reinforcement. He called this material "ferciment". [33]. But at that time in 1850 the technology could not accommodate the time and effort required to make mesh of thousands of wires, but large diameter rods were used to make what is known now as reinforced concrete and the concept of ferrocement was almost forgotten for one century.

In 1940 the Italian engineer-architect Pier Luigi Nervi resurrected the concept of ferrocement. Nervi established the preliminary characteristics of ferrocement through a series of tests. Nervi pioneered the architectural use of ferrocement in buildings. In 1947, he built a small store-house of ferrocement. He also covered the swimming pool of the Italian Naval academy with 15 m vault and the famous Turin Exhibition Hall with a roof of 91 m span [33,34,35].

In the 1960s developed countries such as Australia, the United Kingdom and New Zealand began to use ferrocement as a boat building material. The developing countries became more concerned with the use of ferrocement as a general structural material because of the availablity of the basic components of ferrocement and the low skill needed for construction. The United Nations Industrial Development Organization supervised the building of a ferrocement boat in 1969. In the Soviet Union the first ferrocement structure was built with vaulted roof over a shopping center in Restnikov street, since then the ferrocement was used for roofing unsupported spans varying from 24 m to 30 m [4,33,34,35].

In 1972, the National academy of Sciences (NAS) of the United states of America established an Ad Hoc Panel to study the use of ferrocement in developing countries under the chairmanship of professor James P. Romualdi of Carnegie-Melon University, USA. The final report of the panel was published in 1973 which aroused interest and had immense impact of ferrocement applications. Also in 1972 the Food and Agricultural Organization (FAO) sponsored an international seminar on design and construction of ferrocement fishing vessels in Wellington, New Zealand. In 1974, the American Concrete Institute (ACI) set up the Committee 549 on ferrocement to review the present state of the art, study the engineering properties, practical applications, construction practices, develop guidelines and formulate a code of practice for ferrocement, the report of the committee was published in 1982 [4,33,34,35].

An important development was the establishment of the international ferrocement Information Center (IFIC) at the Asian Institute of Technology, Bangkok, Thailand in October 1976 which started to publish the journal of ferrocement with the collaboration of the New Zealand ferrocement marine Association (NZFCMA) [4,33,34,35].

Ferrocement as a Repair Material

Ferrocement was used as a repair material for different types of structures such as water tanks, relining of tunnels, swimming pools, culverts and chimneys. More than a dozen buildings including factories, offices and residences have been water proofed with ferrocement and since then all of these structures are still performing well. Ferrocement is a material of paradoxes. Ferrocement is a forgiving material, it has a high level of performance in ductility, strength, toughness, durability and crack resistance greater than that found in other forms of concrete construction. The high level of performance in ductility, strength and other properties can be achieved even if quality control is not up to standard. Certainly good quality control leads to better quality and performance. Ferrocement was used as a material for renovation and succeeded commercially in United states especially in rehabilitating water containing structures. Ferrocement provides higher tensile and flexural strengths with numerous fine cracks at an average width of less than 0.01 mm which is very small compared to reinforced concrete which develop few cracks but wider. Ferrocement resists thermal changes efficiently and has mechanical properties which are essentially similar to that of original concrete, this mean ferrocement is thermally compatible with the original concrete and considered a good material for repair. Ferrocement provides a highly impervious layer, it can be safely adopted for water proofing treatment of reinforced concrete structures. [36-42]

Leakage of water through the wall and base of reinforced concrete and masonry tanks is a problem which is faced by field engineers quite frequently. In India, construction of overhead reinforced concrete tanks is mostly entrusted to specialist construction agencies having long experiences in tank construction but inspite of this precaution, many tanks develop leakage through their base or walls immediately after their construction or after a short time of their commissioning. Epoxy patching, silicate mixed, mortar covering of affected areas, guniting are the methods generally used for repairing such leakages. Mortar covering has not proved to be very effective and durable. Epoxy application is a difficult task and bonding of epoxy over an improperly prepared or a damp surface in such areas is highly unsatisfactory. Guniting is a costly treatment and its facilities are not easly available. Ferrocement is a material known for its high impermeability and ease of application on any surface. Ferrocement was used as a repair material for different types and large structures. Architect Jorn Utzn was the first who reported about using of ferrocement as a water proofing layer in New Sydney Opera House in Australia. The Structural Engineering Research Center in India carried out field and laboratory investigations from which ferrocement was recommended as a water proofing material for old and new structures. In the United Kingdom, ferrocement was used for the renovation and relining a sewer system of 60 m length, 2.6 m width and 2.4 m height, inspite of the small layer of ferrocement which was 35 mm it was claimed to be capable of supporting half the load from london traffic above. In New Zealand, an old brick factory chimney was rehabilitated with a new outside skin of ferrocement. A 50000 gallon reinforced concrete overhead circular water tank was treated using ferrocement. This water tank was constructed by the Military Engineering Services, Roorkee in 1971 at Roorkee containment and was abondoned after sometime due to very heavy leakage through the wall of the tank. In 1982 Military Engineering Services approached Structural Engineering Research Center, Roorkee for suggesting a treatment which could be applied to this tank to bring it back to a serviceable condition. After studying the problem in detail, the Center suggested the use of ferrocement for lining the tank from inside after treating the cracks and honeycombed areas. The work was carried out on an experimental basis. After treatment, the tank was filled with water and the external surface of the tank was inspected regularly at intervals of 24 hours, 3 days, 7 days, 14 days, 28 days, 90 days and 365 days, no leakage was observed. The tank has been in service since then with 100% efficiency. Recent applications of ferrocement as a means for relining deteriorated swimming pools strongly suggest that ferrocement is a highly cost competitive solution which also provides a tough, water tight surface that dose not reflect existing cracks in the original structure. In addition to its use as a relining system for swimming pools, experience to date suggests its applicability to a variety of rehabilitation projects from water treatment plants to tunnel linings. [36-42]

Polymer Modified Cementitious Mortar

Since the early 1950, it has been known that addition of certain polymers to cementitious mortar helps to overcome many of the problems of using cementitious mortars as concrete repair materials. Over the past twenty years, many different polymers have been used in a range of applications in the repair and maintenance of buildings and other structures. Such polymer mortars provide the same alkaline passivation protection to the steel as do conventional cementitious materials, and can readily be placed in a single application of 40 to 50 mm thickness which gives adequate protective cover. The polymers are usually used as admixtures and they are supplied as milky white dispersions in water and are used to gauge the cementitious mortar as a whole or as partial replacement of the mixing water. The polymer serves as a water reducing plasticizer producing a mortar with a good workability and lower shrinkage at lower water cement ratios. It reduces the permeability of the repair mortar to water, carbon dioxide and oils and also increases its resistance to some chemicals. It improves the bond between the repair mortar and the old concrete. It increases the tensile and flexural strength of the mortar [6,23-26].

There are different types of polymers which are usually used as a modifier for cementitious mortars. Most of which are manufactured specifically as admixtures . These include Polyvinyl acetates (PVAC), Styrene Butadine (SBR), Polyvilidene dichloride (PVDC), acrylics and modified acrylics. Styrene Butadine (SBR). Acrylic and modified acrylic latexes are most commonly used as admixtures in concrete repair mortars , and when they are properly formulated for compatibility with cement, they do not appear to be any significant differences in the long-term performance of the repair mortars based on the previous three latex types used for general concrete repair. A recent development in the field of polymer is a redispersible spray-dried polymer powders which may be factory blended with graded sand, cement and other additives to produce mortars and bonding coats simply by the addition of water on site [6,23-26].

2.2.2 Epoxy-Resins

Historical Development of Epoxy-Resins

Cementitious materials should be used and considered for repair before any other repair materials, but some times it is very difficult and often impossible to retain sufficient moisture in a shallow concrete repair to ensure full cure of the cement matrix. Also for injecting cracks, it is too difficult and some times impossible to use cementitious repair materials. In these situations epoxy-resins must be used.

Epoxy-resin compounds are used worldwide in the concrete industry as a repair material, for crack injection, coating, bonding agents, sealants, patching materials, general adhesives, binders, water proofing and grouts.

The word "epoxy" is of Greek derivation. The Greek word "epo," which means "on the out side of," was combined "Oxygen" which describes the presence of the oxygen atom in the molecular structure. In short, the word is a Greek description of the chemical symbol for the family of epoxy [43].

The first practical application of epoxy resin took place in Germany and Switzerland in 1930s. The first known patent on epoxy was issued to Dr. Pierre Casan in Switzerland in 1936. Three years later, Dr. S.O.Greenlee of United States explored and developed several basic epoxy systems, many of which are used today as adhesives and coatings. In the late 1940s the production of epoxy resins started and in 1950s it was produced commercially. The first use of epoxy as a bonding agent between two pieces of hardened concrete was in 1948, it gave a satisfactory structural adhesion with the capability of being stronger than the bond of concrete itself [43].

In 1954 the California Highway Department became interested in epoxies as a bonding agent for raised traffic lane markers on concrete highways. The successful utilization of an epoxy as a bonding agent encouraged the extension of research into the field of structural repair of concrete and the eventual application of an epoxy polysulfide polymer, as a bonding material for joining new concrete to old [43].

Epoxy injection systems were first used for a structural grouting and repair in the late 1950. The approach was to premix epoxy and then pump the mixed epoxy system. The injection of epoxy into structural cracks permitted for the first time a positive technique for restoration of the structural integrity of cracked concrete. In 1960 a system was developed utilizing pressure injection with a mixing head at the nozzle of the injection gun which expanded the applications of epoxy as a grouting adhesive in structural concrete. In the late 1950 epoxy was first attempted as a grout to bond bolts or dowels to hardened concrete. Epoxy grout has also been successfully used for installation of hand rails, architectural metals, precast concrete panels, structural concrete and steel members, concrete railroad ties, and for numerous other applications [43].

In the field of seal coating, epoxy seal coating was first applied as test patches in industrial plants in 1953 and on highways in 1954. Epoxy concrete was first used as a wearing course in the repair popouts and spoiled areas on the surfaces of various concrete bridge decks in california in 1957. Presently epoxies are used widely with concrete in the form of bonding agents, adhesives, coatings, paints, repair materials, epoxy mortar and concrete, wearing surfaces and seal coats [43].

Uses and Applications of Epoxy

Several investigations have been carried out on the uses and applications of epoxy compounds with concrete. For instance, ACI Committee 503 [43] published a report entitled "Use of Epoxy Compounds with Concrete". This report provides a detailed review of literature on epoxy history, chemical and physical properties of epoxy, characteristics, precautions, guidelines to users, uses and preparing surfaces for repair. Chung [44] used epoxy for repairing reinforced concrete beams. The results showed that, the integrity is restored by the repair process, the flexural strength of the repaired beams was not less than the original beams, the repaired cracks do not reopen even at failure of the beam and the repaired beams are stiffer than the original beams. Investigation by Chung and Lui [45] showed that the shear stress and deformation in the repaired beams was not less than the original concrete beams. Studies carried out by Chung [46] further showed that the bond strength and bond stress of the repaired members were similar to those in the original concrete members. In an investigation carried out by Mansur and Ong [49] it was found that cracks did not reopen at ultimate load in the epoxy repaired beams. The maximum crack widths in the repaired beams were less than those in the original beams and the repaired beams were stronger and stiffer than the original beams.

A new technique was developed for repairing cracked structural bridge concrete by epoxy in 1977 by Kansas Department of transportation under contract to Federal Highway Administration [47].

Specification for repairing concrete with epoxy mortars were established by ACI Committee 503.4.79 [48]. These standard specifications describe the work of repairing defects in hardened cement concrete with a sand-filled mortar using an adhesive binder such as that defined in ASTM C 881. It include controls for adhesive labeling, storage, handling, mixing and application and surface preparation as well as inspection. The British Standard Institution (BSI) provides a British Standard for epoxy (BS 6319 : 1983) under the title "Testing of resin composition for use in construction". Also the American Society of Testing and Materials (ASTM) provides a Standard Specification (C-881-78 and reapproved in 1983).

bi; Performance of Epoxy under Fire and Hot Weather Conditions

The behavior of structural elements repaired with epoxy under fire was studied by different researchers. Plecnik et al [50]. showed that the cheaper small-scale specimens can be effectively used to study the behavior and mechanical properties of epoxy repaired concrete walls subjected to fire exposure rather than full-scale specimens. Their results showed that the strength of epoxy adhesives rapidly decreases at a temperature above 110°C , with near zero strength at a temperature above 204°C (400°F). Investigation carried out by Joseph [51]. showed that, in the shear type epoxy repaired cracks, the strength and stiffness are primarily determined by epoxy strength which is negligible above 204°C (400°F). For the flexural type epoxy repaired cracks with out compression zone failure, the strength of the beams is not affected by epoxy repair but stiffness is greatly reduced with increasing temperature. Another study by Joseph Plecnik, John Plecnik, Parra and Diba [52]. showed that the strength, stiffness and bond become negligible above $204°C$ $(400°F)$.

The performance of epoxy in hot weather conditions was investigated at King Fahd University of Petroleum and Minerals [53]. The results of this study indicated that, hot weather conditions of Gulf region are considered adverse effects on epoxy-injected concrete, not all the epoxies can perform satisfactorily in the hot weather conditions of the Gulf. Only special types of epoxies should be used to resist these conditions.

Advantages of epoxy resins

There are many advantages of using epoxies in concrete. Some of the properties of epoxies which make them desirable for use in concrete are:

(1) Adhesion; epoxies form excellent and very strong bond with concrete

(2) Versatility; exhibited by a wide range of their physical and chemical properties.

(3) High resistance to the attack of acids, oils, alkalies and solvents.

(4) Rapid hardening, low shrinkage and highly impermeable to water.

Disadvantages and Precautions of epoxy resins

Some of the disadvantages of using epoxy resins are:

(1) Strain Compatibility.

(2) The large differance in the coefficients of thermal expansion between concrete and epoxy.

(3) Thermosetting Plastic Property.

(4) Need for skilled labors.

CHAPTER 3

EXPERIMENTAL PROGRAM

3.1 Test Program

This chapter outlines the experimental work carried out to meet the objectives of this research. The experimental work can be broadly classified into the following four tasks as shown in the charts on the following pages.

(1) Determination of water permeability, chloride permeability and corrosion resistance of normal concrete samples and those prepared using repair materials (Ordinary cement mortar, Ferrocement mortar, Polymer modified mortar and Silica fume mortar).

(2) Casting of reinforced concrete beams and repairing them using three repair materials.

(3) Monitoring the corrosion of rebars in normal concrete and repaired

CHART PROGRAM OF THE STUDY

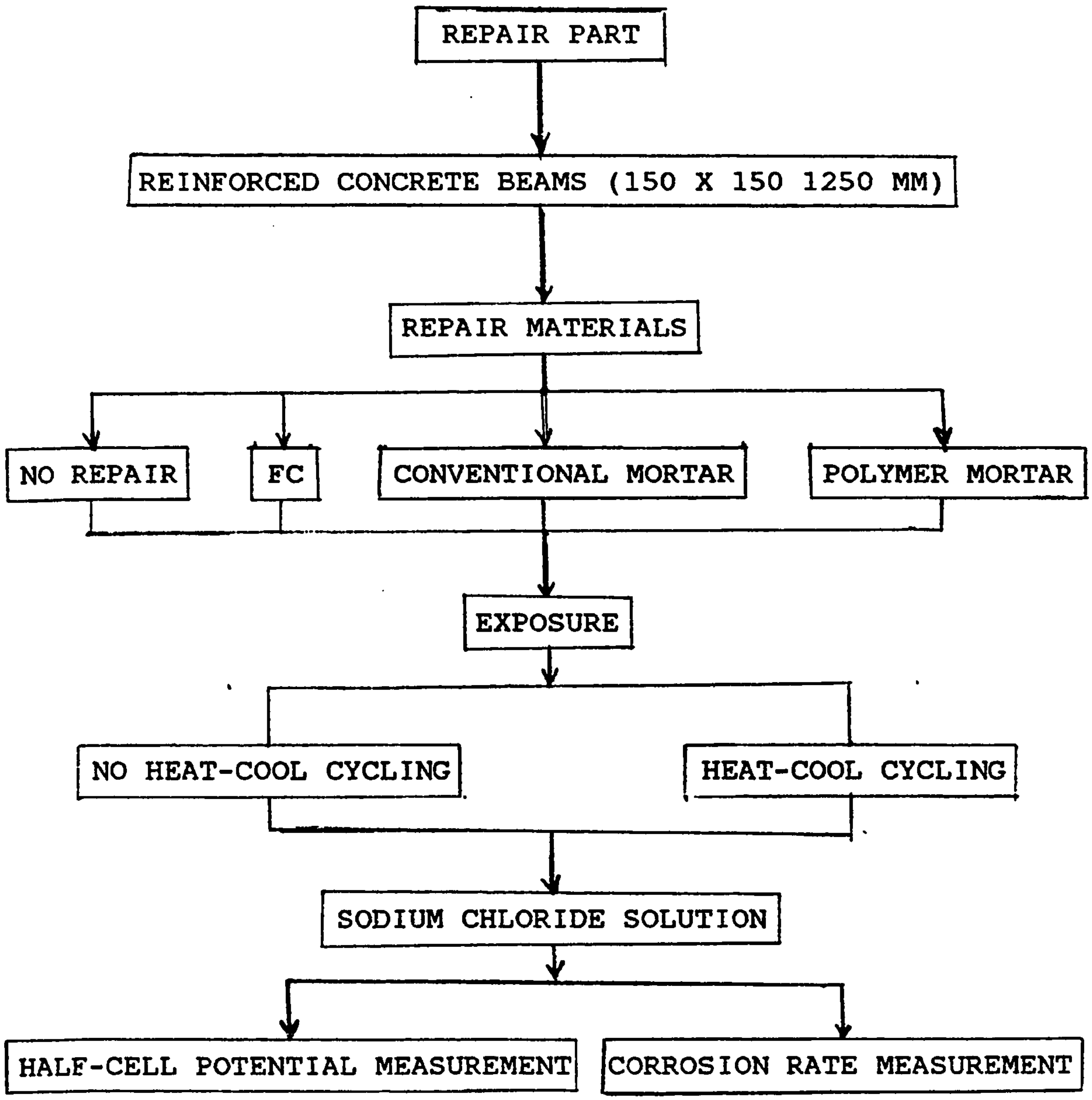


CHART PROGRAM OF THE STUDY

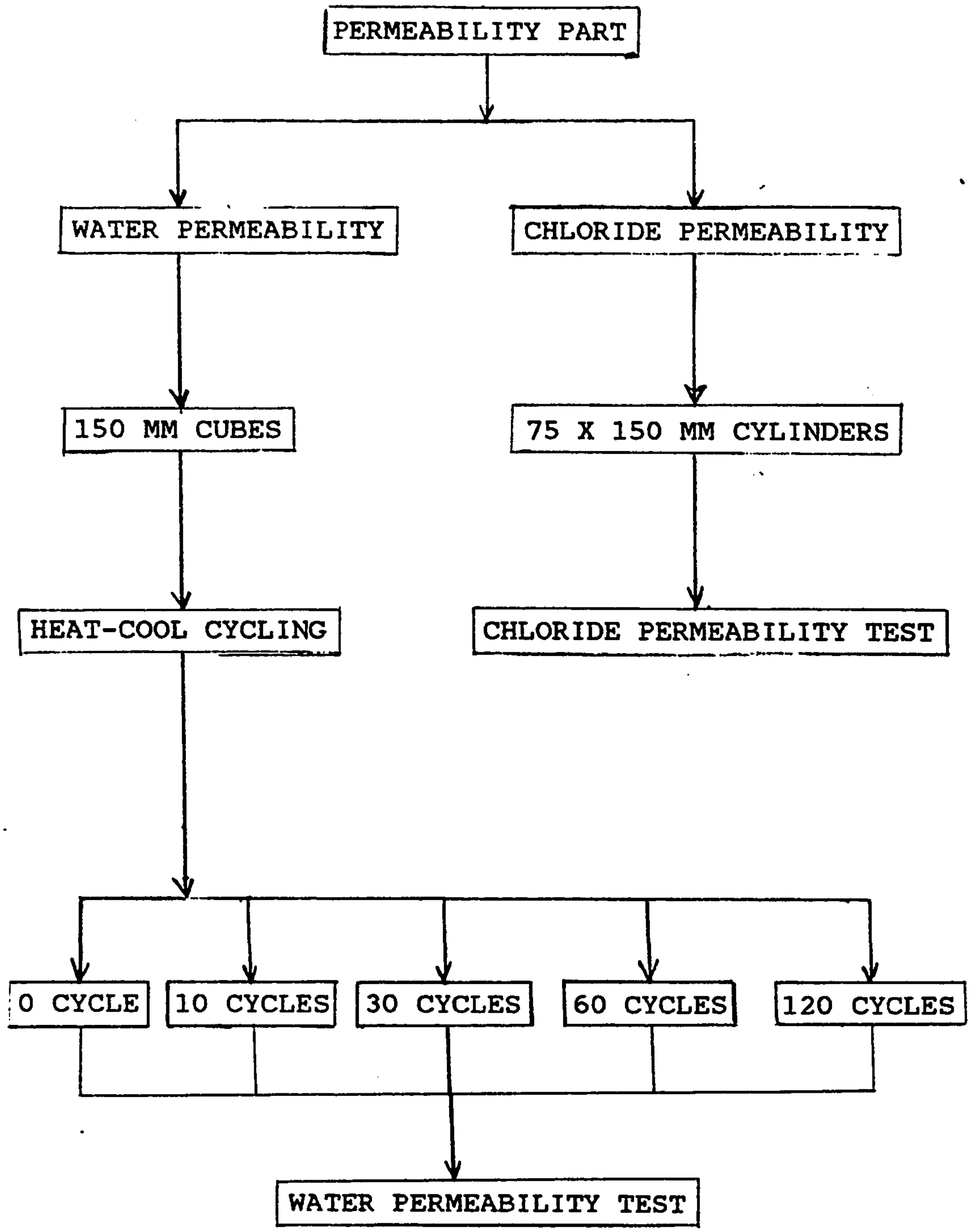


CHART PROGRAM OF THE STUDY

ACCELERATED CORROSION BY IMPRESSED CURRENT

↓

62.5 X 100 X 300 MM PRISMS

↓

IMPRESSED CURRENT TEST

concrete beams.

(4) Evaluating the effect of heat-cool cycling on the permeability and corrosion resisting characteristics of normal concrete specimens and those prepared using the repair materials.

In order to achieve the objectives of this test program more than 300 concrete specimens were cast and tested. Table 3.1 shows the type and number of specimens cast for carrying the test program. The following paragraphs detail the experimental work carried out in this investigation.

3.2 Reinforced Concrete Beams Tests

3.2.1 Casting of Reinforced Concrete Beams

Reinforced concrete beams 150 x 150 x 1250 mm were cast using concrete with water cement ratio of 0.48 and whose composition is shown in Table 3.2. Two 10 mm diameter steel bars were used as bottom bars, and two 6 mm diameter bars were used as top bars. 6 mm diameter bars were used as stirrups at a spacing of 60 mm throughout the length of the beam. In order to carry out corrosion measurements, copper wires were soldered to all the longitudinal bars. The connections were sealed with a silicon sealant to avoid galvanic corrosion of the rebars in case of moisture ingress. The details of the steel reinforcement and location of the connections are shown in Figure 3.1 and Plates 3.1 and 3.2 .

Steel molds were used for casting the beam specimens. Before pouring the concrete, the molds were cleaned and oiled. The reinforcement

Table 3.1 Type and Number of Samples Cast and Tested in This Investigation

Type of test	Type of Samples	Dimension (mm)	No. of Samples
Corrosion and Heat-Cool Cycling	R.C. beams	150x150x1250	24
Corrosion by Impressed Current	Prisms	62.5x100x300	18
Water Permeability	Cubes	150x150x150	90
Chloride Permeability	Cylinders	75x150	24

Table 3.2: Quantities of Materials Used for Casting Reinforced Concrete Beams

Cement Content (Type V)	400 Kg/m^3
Coarse Aggregate (Abu hadriah)	1073 Kg/m^3
Fine Aggregate (Local Dune Sand)	651 Kg/m^3
Water	192 Kg/m^3
Air Content	2 %

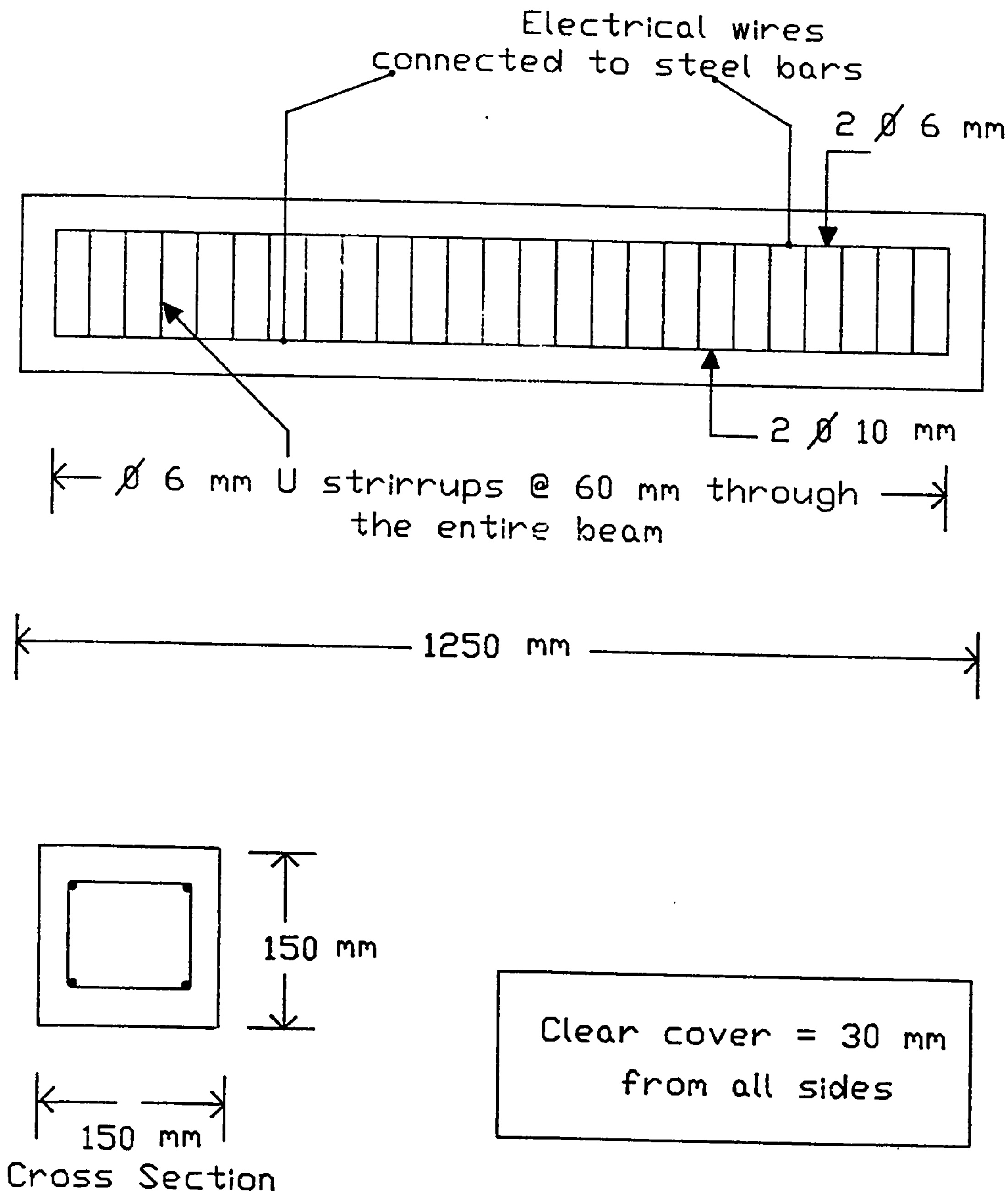


Fig. 3.1 Details of Beam specimens

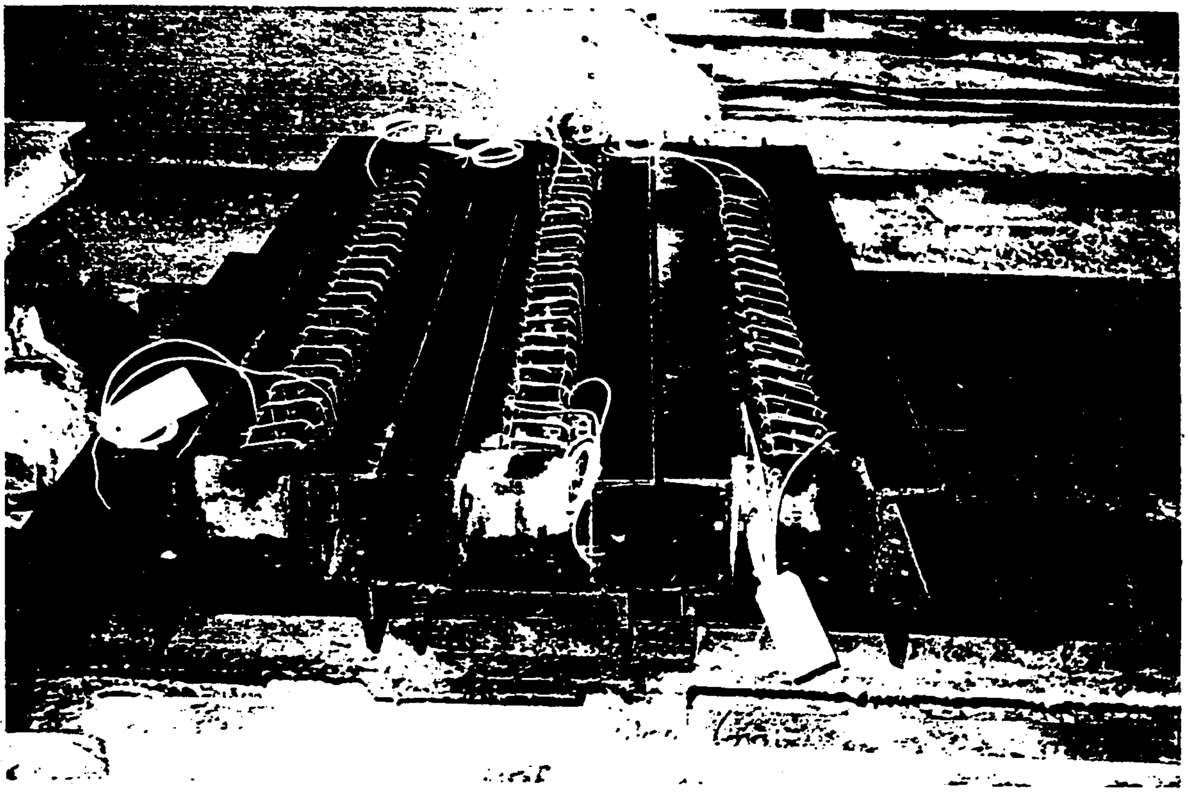


Plate 3.1 Beams before Casting

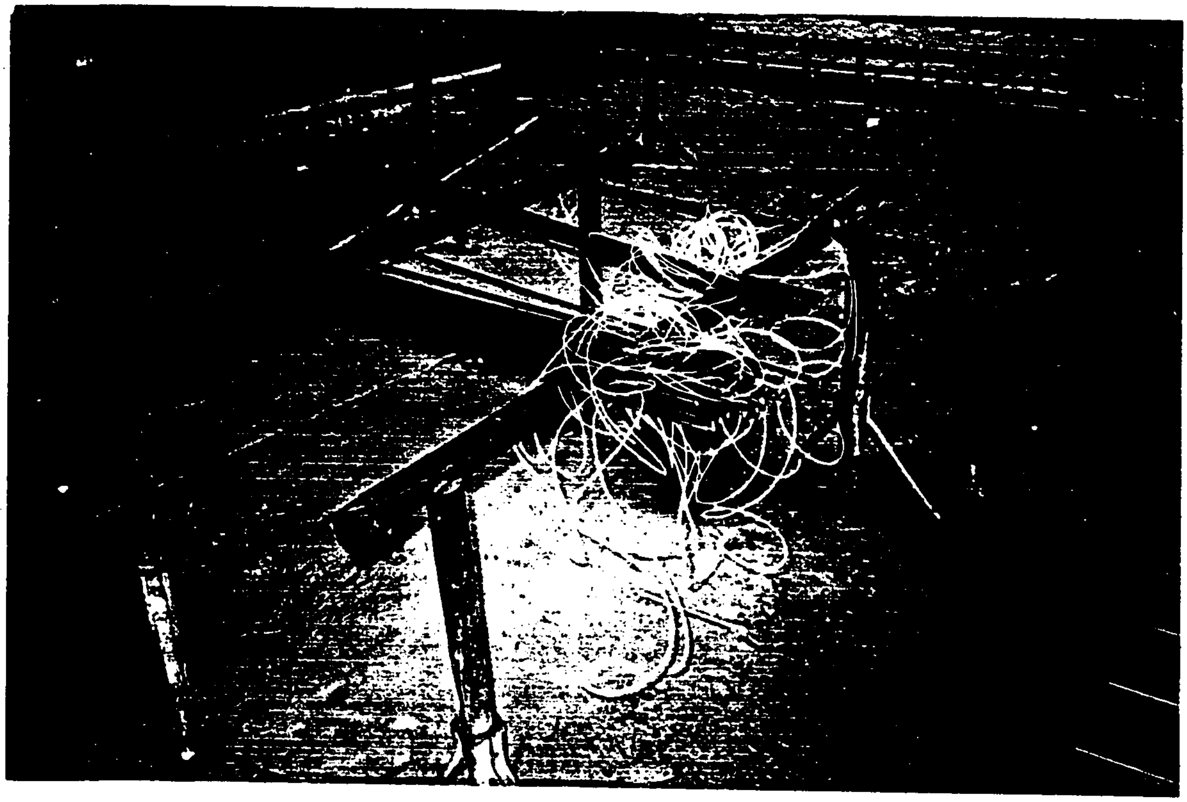


Plate 3.2 Electric Wires connected to the reinforcing bars.

cage was then placed in the molds. Plastic spacers were used to provide a cover of 30 mm on all the sides.

The concrete ingredients were mixed in a mechanical mixer. After the predetermined mixing time (which was 5 minutes), the concrete was placed in the molds and compacted by using a vibrating table. The molds were filled in two layers. The workability of the concrete was checked by measuring the slump of each batch.

Four concrete cylinders 150 x 300 mm from each batch were cast in three layers according to ASTM C-192 to determine the compressive strength of each batch.

After casting the beams and cylinders, they were covered with a plastic sheet and allowed to cure for 24 hours. After this period, the cylinders were demolded and placed in a curing tank. The beams were removed from the molds and covered with wet jute burlaps. These jute burlaps were kept damp by spraying water, three times daily. Plates 3.1 through 3.4 show the details of the casting and curing procedures. The samples were cured for 28 days, after this time they were used for the repair work.

3.2.2 Repair of Reinforced Concrete Beams

After curing the beams for 28 days, they were divided into 7 groups, each group consisting of 3 beams. One group was left without repair, to be used as a reference group. The second two groups were repaired with ordinary cement mortar, two groups repaired with ferrocement mortar and

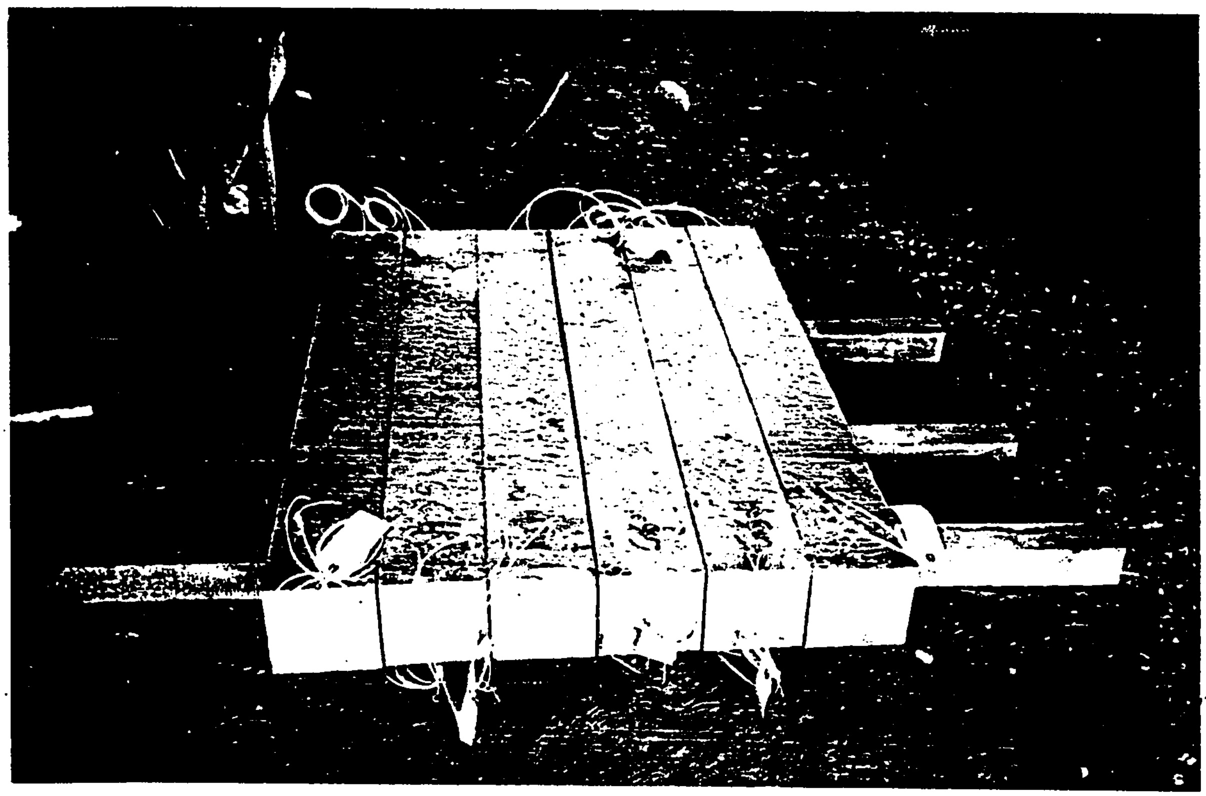


Plate 3.3 Beams After Casting

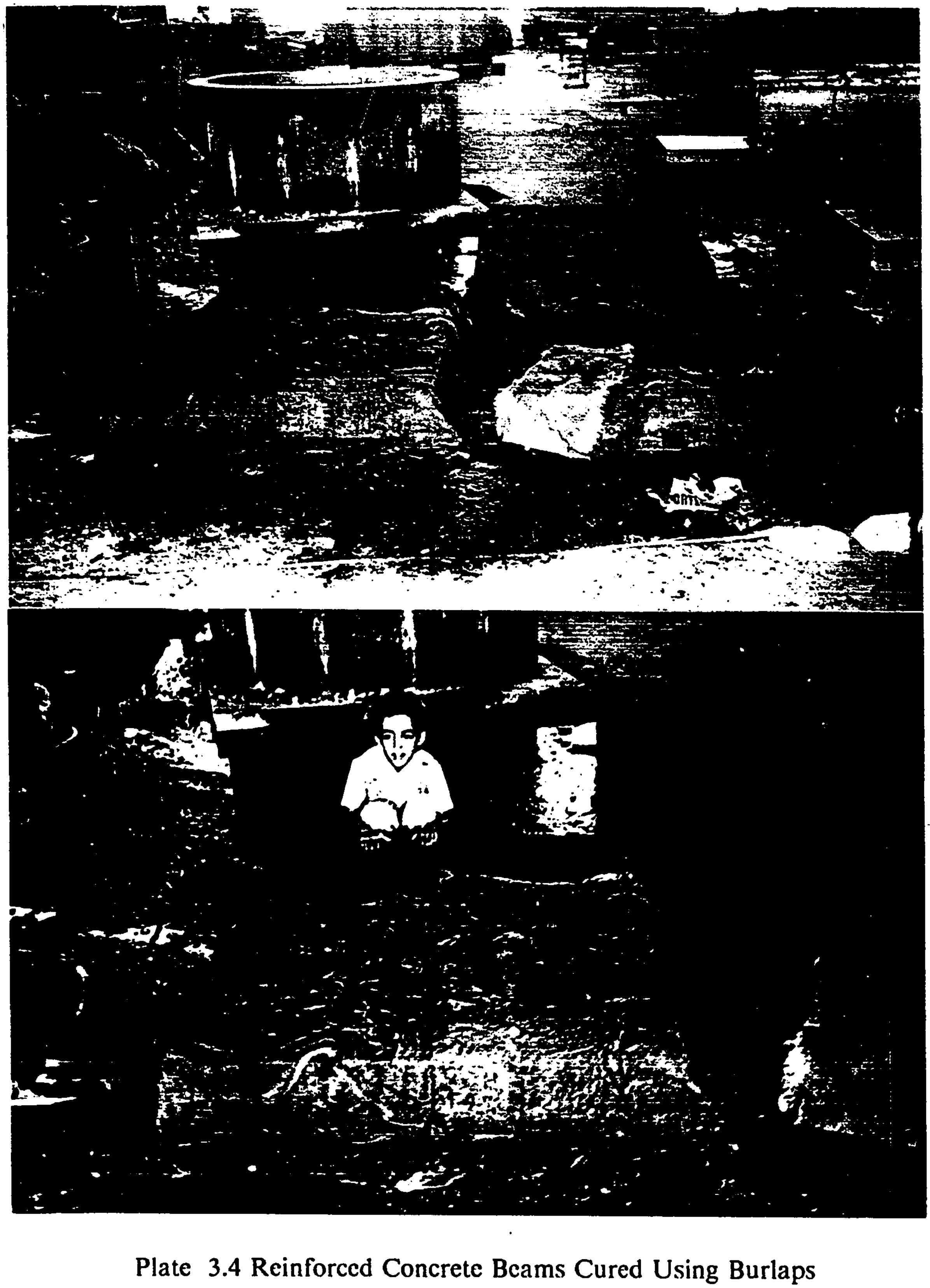


Plate 3.4 Reinforced Concrete Beams Cured Using Burlaps

the last two groups were repaired with polymer modified cementitious mortar. One group from each two groups was placed in a 5% sodium chloride solution and rebar corrosion was monitored, while the other group was subjected to heat-cool cycling and placed in a 5% sodium chloride solution for corrosion monitoring. The bottom concrete cover of the beams was chipped off, till the bottom reinforcement was visible as shown in Plate 3.5. This was done using a hammer and a chisel. The samples were then placed in specially prepared wooden molds, so that. the chipped surface was accessible. The chipped surface was cleaned and roughened to improve the bond between the hardened concrete and the repair material. The beams were repaired using the following methods and materials (Plates 3.5 through 3.7).

Cement Mortar

In this repair method, the chipped beams were placed in the wooden molds and they were cleaned and thoroughly wetted with water. The chipped concrete surface was brushed with a cement paste (cement-water ratio of 1:1) to improve the bond between the repair material and the original concrete. The cement mortar used for repairing the beams was prepared by mixing the ingredients in a mortar mixer. A sand/cement ratio of 2 and water-cement ratio of 0.45 was used for the preparation of the mortar. After mixing, the mortar was placed on the chipped surface and compacted using a vibrating table. The mortar was then levelled using a trowel. The beams were then covered with polyethylene sheets. The repaired beams were cured by spraying water on the repaired face for

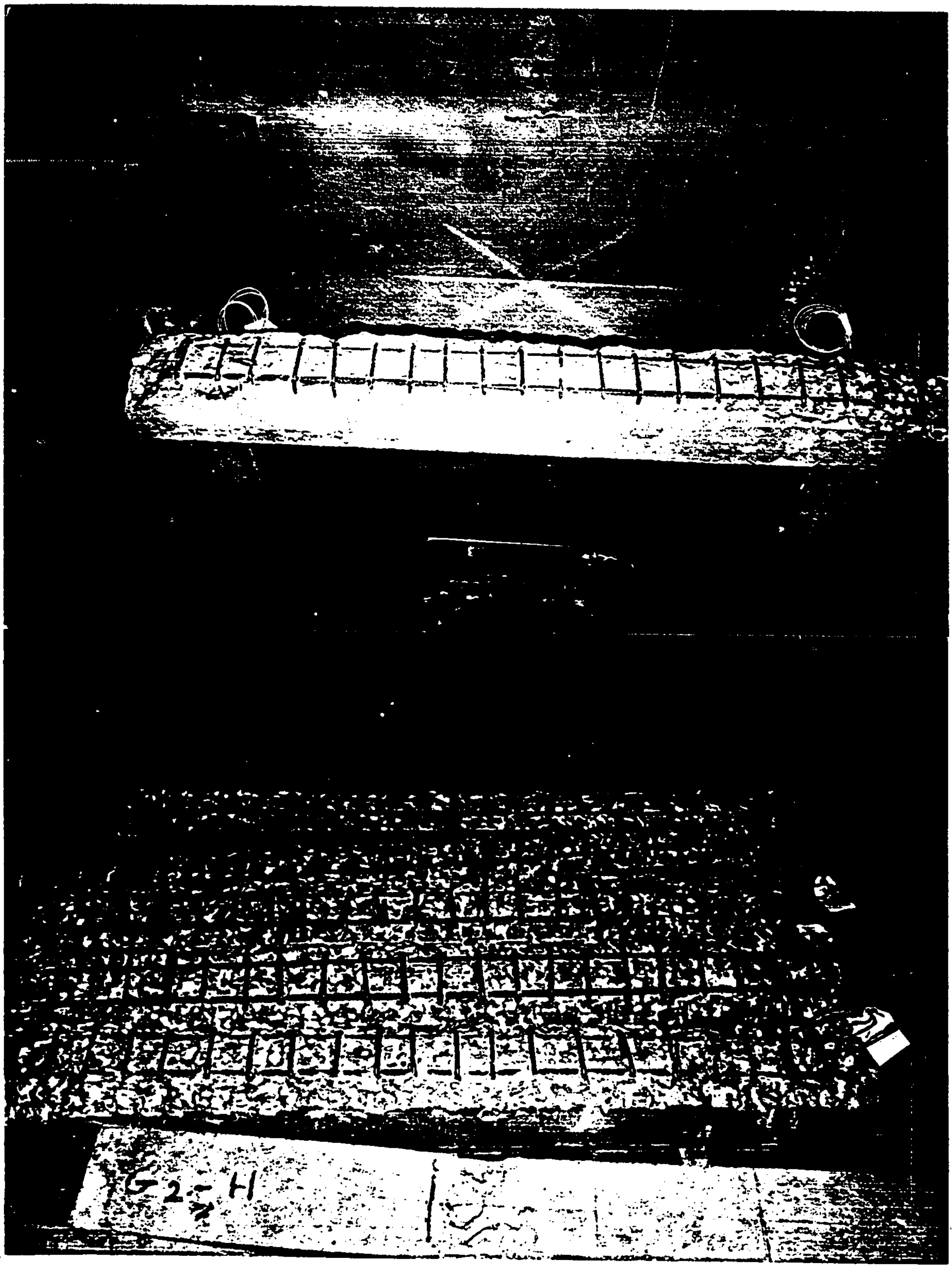


Plate 3.5 Reinforced Concrete Beams with Concrete Cover chipped for Repair.

Plate 3.6 Bonding Agent Applied on the Chipped Surface.

Plate 3.7 Beams After repair

a period of 28 days. The beams repaired with this repair material are designated as OMR if not subjected to heat-cool cycling and as HCOMR if subjected to heat-cool cycling.

Ferrocement Repair

The chipped surface was cleaned and then wetted thoroughly with water. A cement paste (water-cement ratio 1:1, used as bonding agent) was applied on the chipped surface. The cement mortar to be used in repairing the beams was prepared by mixing in a mortar mixer. A sand/cement ratio of 2 and water-cement ratio of 0.45 was used in the preparation of the mortar.

After mixing, the mortar was placed on the chipped surface to partially cover the chipped depth of the beam. A wire mesh, consisting of 0.9 mm diameter galvanized steel with 7.54 mm square opening and 414 Mpa ultimate strength, cut to proper size was then placed on the fresh mortar. The remaining depth of repair was then filled with mortar and the beams were vibrated to compact the material. The surface of the repair material was levelled using a trowel. The beams were then cured by spraying water on the repaired face for a period of 28 days. Beams in this category are designated as HCFCR and FCR for the cases with and without heat-cool cycling respectively.

Polymer Modified Cement Mortar

In this repair method, polymer modified cement mortar was used as a repair material. A special product was used as a bonding agent (Plate

3.6). This special product is polymer emulsion which is a milky white liquid. This bonding agent was prepared by mixing this special product with water and cement in a ratio of 1:1:6 by weight. The chipped surface was first cleaned, saturated throughly with water and then the bonding agent was applied using a brush. The polymer modified mortar was mixed using special type of mixer and placed on the chipped surface and compacted using a vibrating table. The repaired beams were covered with damp burlaps immediately after repairing. The beams were demolded after 24 hours and cured for further 28 days by spraying water three times daily.

3.2.3 Heat-Cool Cycling

Three repaired beams from each repair category were subjected to heat-cool treatment in order to evaluate their performance in a simulated conditions of the Arabian Gulf environment. The heat-cool cycles were designed to represent daily and seasonal variations in the ambient temperatures in this part of the world. The beams were placed in an electrical oven as shown in Plate 3.8. The temperature was raised gradually till it reached a maximum temperature of 80°*C*. It took about 4 hours for the oven to attain this temperature. The oven was maintained at 80°*C* for two hours, and then the temperature was gradually decreased to room temperature in four hours. The oven was maintained at room temperature for two hours, before another heat-cycle was initiated. The repaired beams were subjected to 60 heat-cool cycles. The beams were then placed in 5% sodium chloride solution for corrosion monitoring.

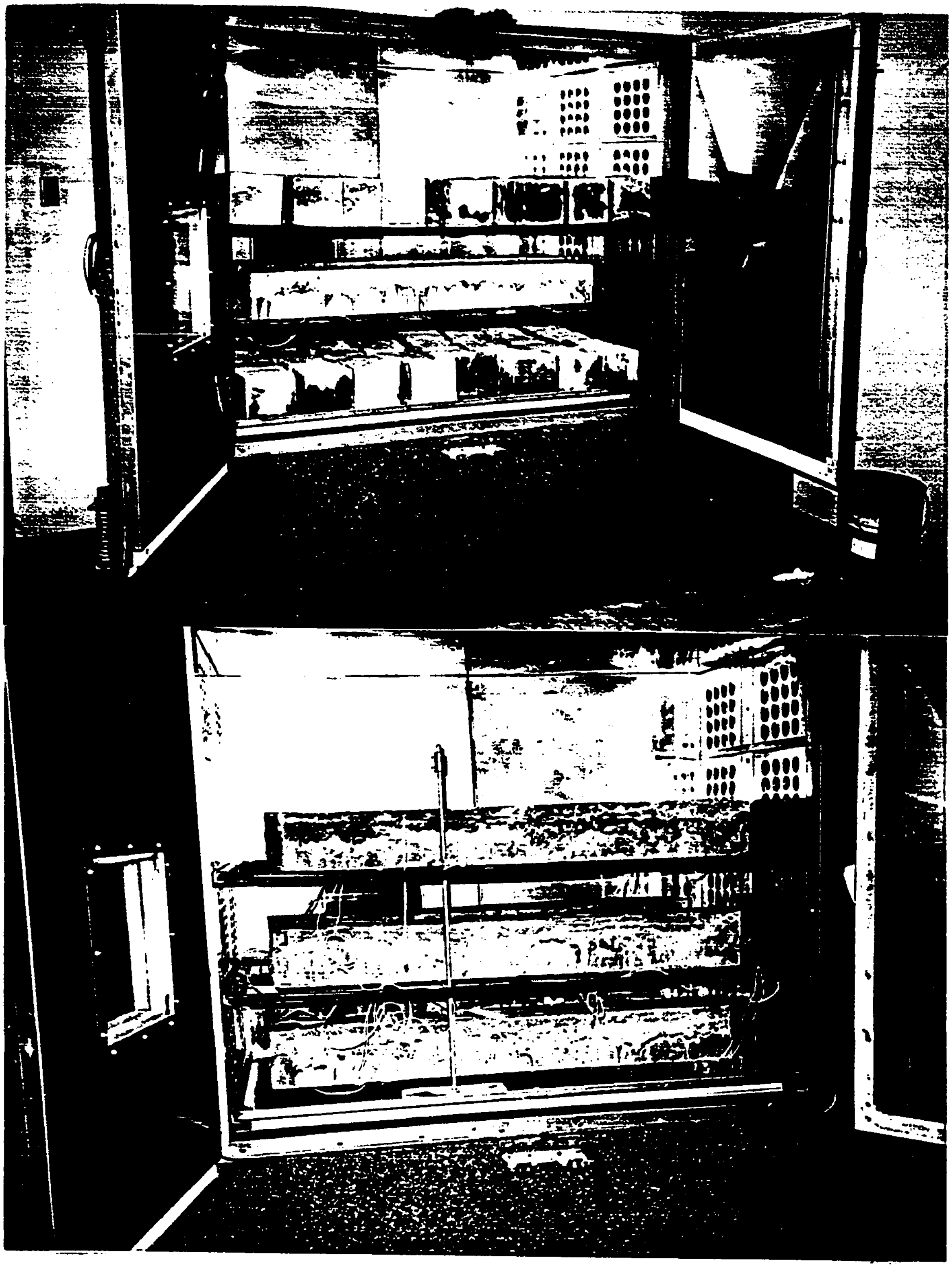


Plate 3.8 Beams and Cubes in the Oven for Heat-Cool Cycling

3.2.4 *Corrosion Monitoring*

The main aim of this investigation was to study the corrosion-resisting characteristics of beams repaired using various repair materials. Three beams from each repair category without heat-cool cycling and three beams with heat-cool cycling. The repaired samples along with control beams were partially immersed in fibre glass tanks containing 5% sodium chloride solution. The level of the chloride solution was adjusted, so that only 5 cm of the bottom beam was in the solution (Plate 3.9). The concentration of the sodium chloride solution was monitored and adjusted each week. The techniques used to monitor the corrosion activity of rebars in the repaired and control (not repaired beams) beams are discussed in the following paragraphs.

Half-Cell Potential Monitoring

All reinforced concrete beams (repaired and control) were partially immersed in 5% sodium chloride solution and connected to a data logger for monitoring half-cell potentials against saturated calomel electrode (SCE). The top and bottom bars from each beam were connected to the positive terminals of a Tokyo Sokki Model TDS-301 Data Logger. The connections were made through electrical wires which were soldered to the steel bars before they were cast in the concrete. The negative terminals of the data logger were connected to Saturated Calomel Electrode (SCE) placed in the fibre glass tanks, containing the samples partially immersed in the salt solution (Figure 3.2 and Plate 3.10). The half-cell potentials were read every 24 hours. According to ASTM C 876, if the half-cell

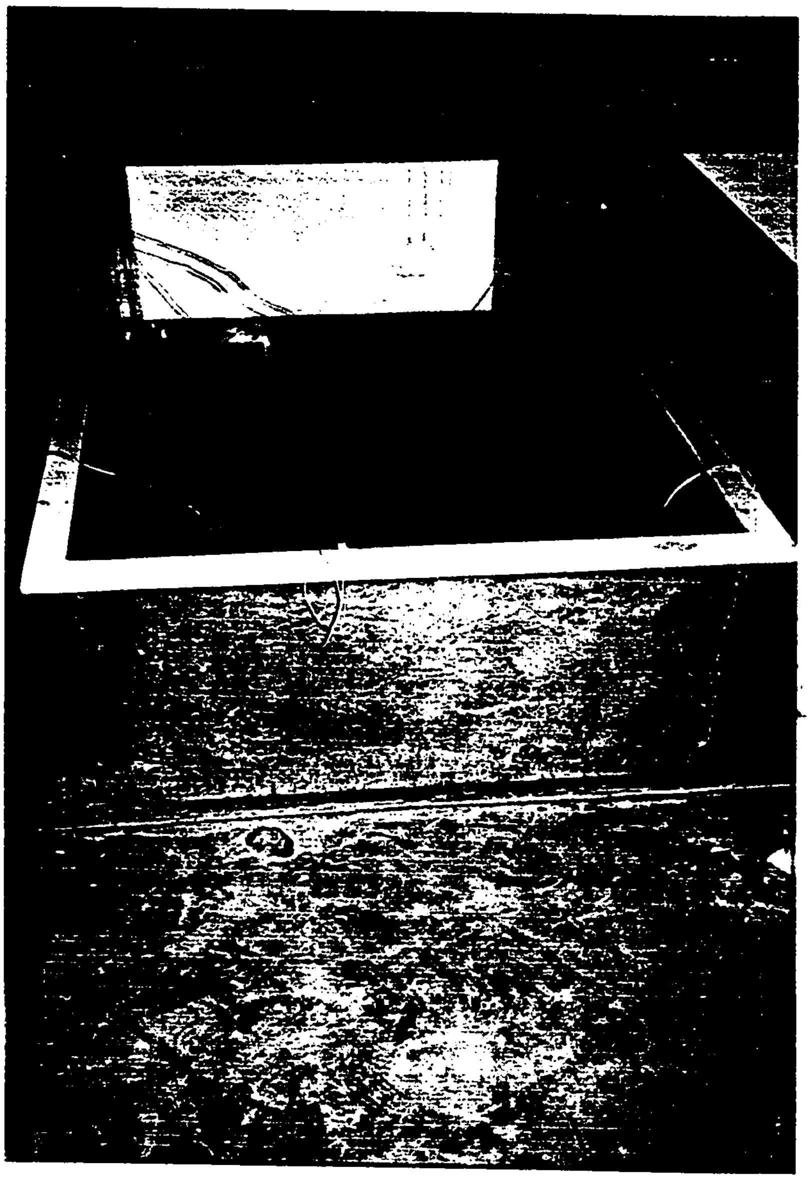


Plate 3.9 Immersion of Beams in Nacl solution.

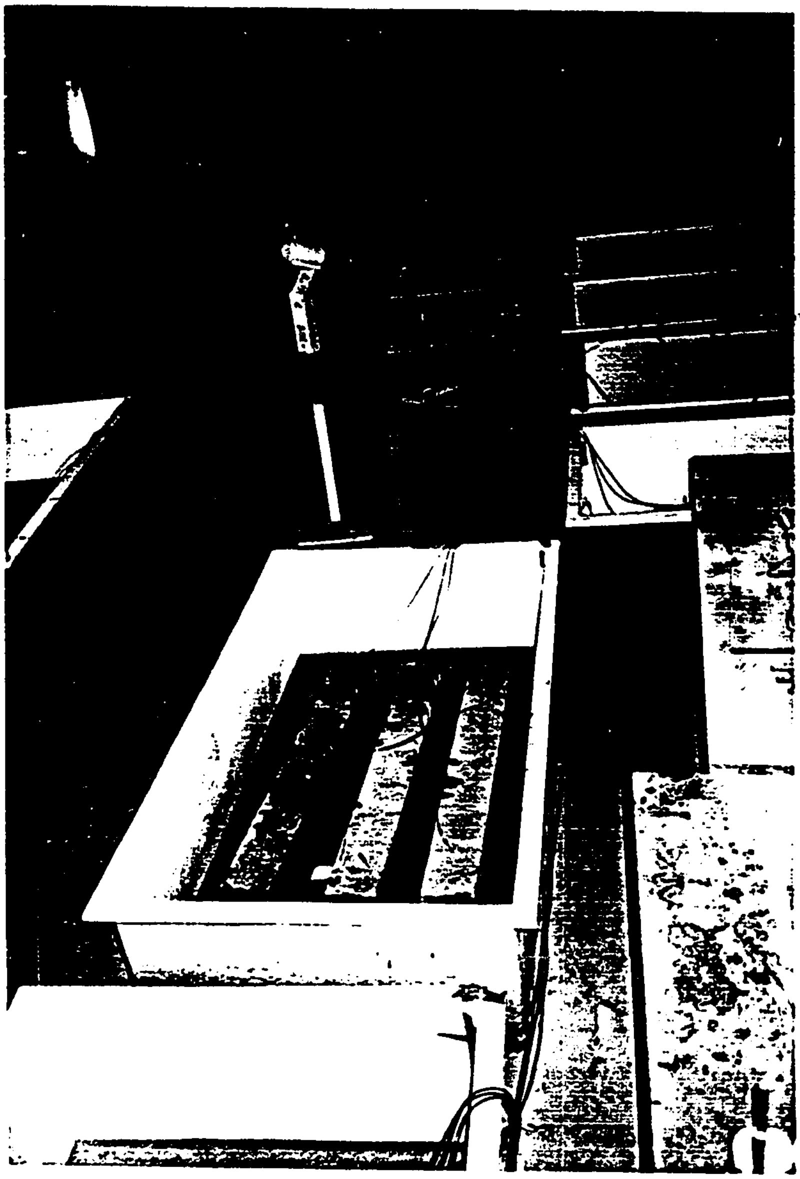


Plate 3.10 Set-up of Half-Cell Potential Monitoring.

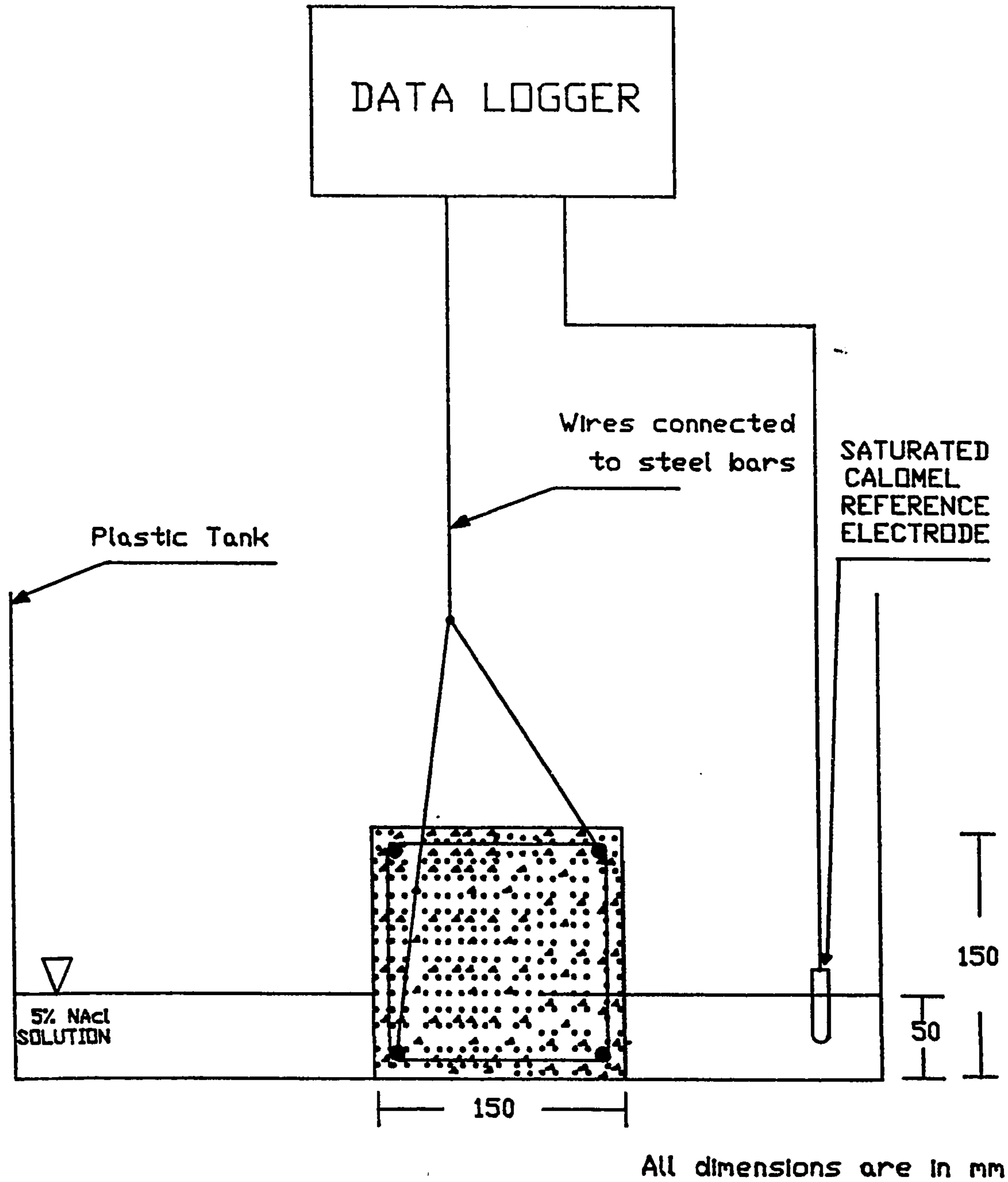


Figure 3.2 Schematic Diagram of Half-cell Potential Measurement Set-up

potentials are in the range of -200 mV to -350 mV against copper copper-sulfate electrode (CSE) i.e., -120 to -270 mV against SCE corrosion of rebars is uncertain. If the potentials are numerically greater than -350 mV CSE (-270 mV against SCE) there is a greater than 90 % probability that reinforcing steel corrosion is occuring. Thus, the half-cell potentials provide a qualitative indication of rebar corrosion.

Corrosion Rate Measurements

In order to evaluate the performance of the repair materials in inhibiting rebar corrosion, it was thought that quantitative data on the corrosion rates should be collected for the beam specimens repaired with different repair materials. In this direction, the Tafel plot and linear polarization resistance and gravimetric weight loss techniques are found to be useful. The gravimetric weight loss technique is a destructive method of determining the rate of corrosion. In a corroding system, the intensity of both the anodic and cathodic currents is equal. As such, the net corrosion is zero or it cannot be measured. In the Tafel technique, the steel is polarized to a certain potential, normally called overpotential and the resulting corrosion current is measured. The experimental set-up usually consists of a working electrode (reinforcing steel in concrete), a reference electrode and a counter electrode (also called an auxiliary electrode). The working electrode is normally polarized in the range of -250 to +250 mV of the free potential or the open circuit potential. The resulting current is plotted on a logarithmic scale against the applied potential on a normal scale. An Idealized Tafel plot is shown in Figure 3.3a. The initial portions

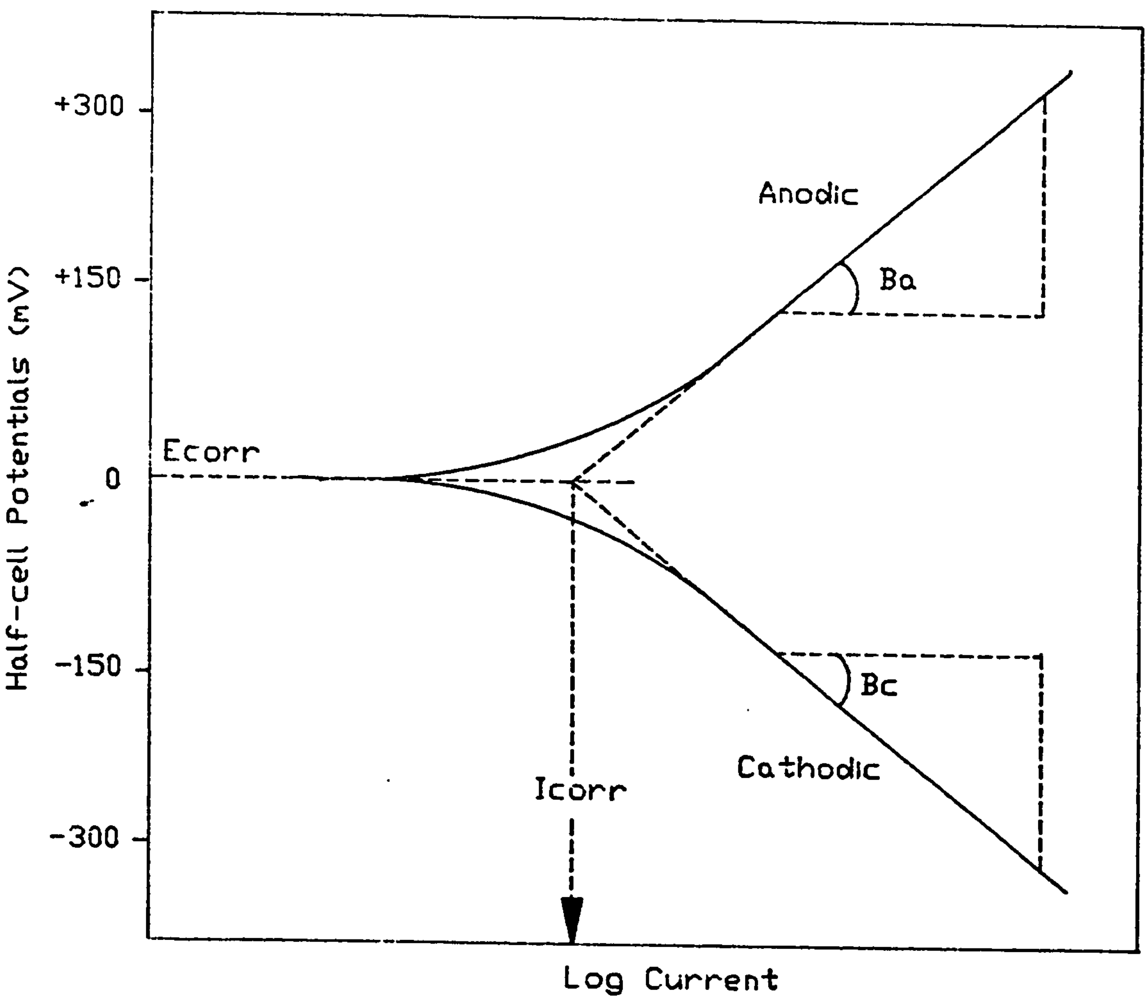


Figure 3.3a: Idealized Tafel Plot

of the anodic and cathodic Tafel plots being linear are extended till they intersect each other. The point of intersection of these two lines on the x-axis denotes the intensity of the corrosion current. The corrosion rate in a metal due to corrosion can then be calculated using the value of corrosion current and the Faraday's law as follows:

$$Corrosion\ Rate = 3.27 * I_{corr} * \frac{E.W.}{d} \ldots\ldots\ldots\ldots (i)$$

Where:

corrosion rate is in μm/year

I_{corr} = *corrosion current in* $\mu A/cm^2$

E.W. = equivalent weight of steel in grams

d = *density of steel in* gm/cm^3

Another technique of determining the corrosion rate is the use of linear polarization technique. In this technique, which was developed by Stern and Gearey [63], the steel is polarized to ± 20 mV of the open circuit potential and the resulting current is measured. Since this plot is normally linear, the resistance to polarization which is the slope of this curve is calculated. The corrosion current is then calculated using the following relationship.

$$I_{corr} = \frac{R_p}{B} \ldots\ldots\ldots\ldots (ii)$$

where:

I_{corr} = *corrosion current in* $\mu A/cm^2$

R_p = *polarization resistance in K-Ohm*

$B = (\beta_a * \beta_{c)} / 2.3 (\beta_a + \beta_{c)}$

where β_a and β_c *are* the anodic and cathodic Tafel constants. These constants are the slopes of anodic and cathodic Tafel plots respectively, as shown in Figure 3.2a

The corrosion rate is then calculated using equation (i).

For steel in an aqueous media, values of β_a and β_c equal to 100 are normally used as a Tafel constant. However, in the absence of sufficient data of the values of β_a and β_c for *steel in concrete a value of B* equal to 52 for steel in passive condition and equal to 26 for steel in active condition are used.

In this investigation data on corrosion rates and the Tafel constants were developed by running the anodic and cathodic polarization scans (Tafel experiments). The samples were polarized to ± 250 mV of the free potential. A Princeton Applied Research Model 279 Potentiostat/Galvanostat (with IR compensation option) was used for this purpose. Figure 3.3b is a schematic representation of the test set-up. A scan rate of 0.2 mV/sec was used. Current interrupt technique was used to compensate for the ohmic drop (IR) between the reference electrode and

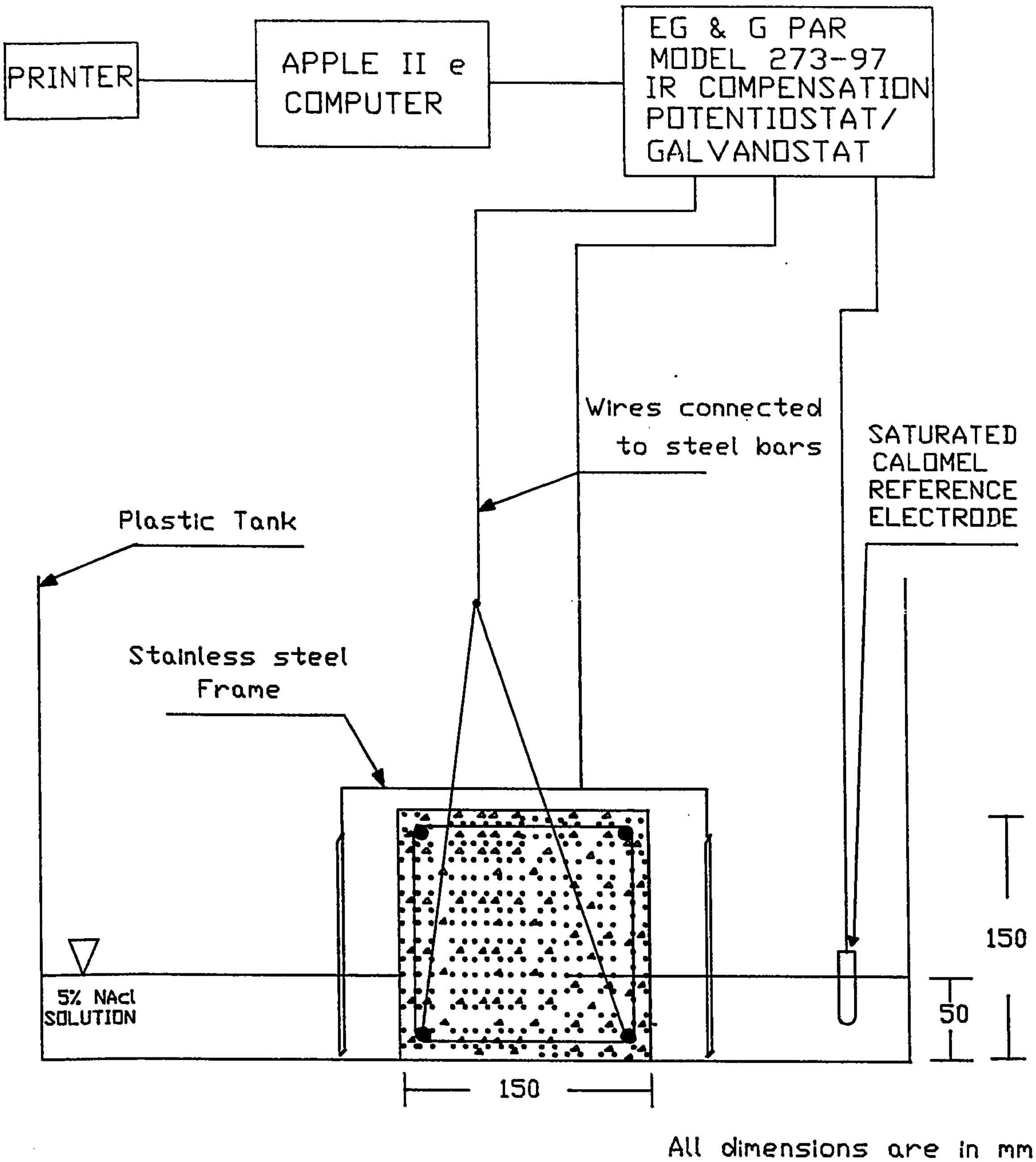


Figure 3.3b Schematic Diagram of Corrosion Rate Measurement Set-up

the reinforcing steel bar. The potentiostat is controlled by an Apple computer (Plate 3.11). The software collects the data and analyzes it to obtain the best fit curve and calculate the values of Tafel constants and corrosion rate (Plate 3.11).

Electrochemical Noise Measurement Technique

Electrochemical noise is observed as spontaneous fluctuations of potential and current in a corroding system. The measurement and analysis of the corrosion potential noise is a technique which can be used for monitoring corrosion both in the laboratory and on site. The noise signal can be obtained between the reinforcement and a reference electrode using a sensitive digital voltmeter. The standard deviation, or r.m.s., of the noise signal appears to be proportional to the corrosion rate. The data collected using this technique can be used to complement the half-cell potential mapping technique. In this investigation electrochemical potential noise data were collected for all the repaired beams. The objective of this endeavor was to analyze this data and compare it with the corrosion data generated using other techniques.

3.3 Corrosion Monitoring by Impressed Current Technique

This technique is used here as a comparative tool to evaluate the performance of the various repair materials with regard to rebar corrosion. The corrosion of rebars is accelerated by impressing a known potential, and the resulting current is plotted against time. In this system the working electrode (steel bar in concrete) serves as an anode and a counter

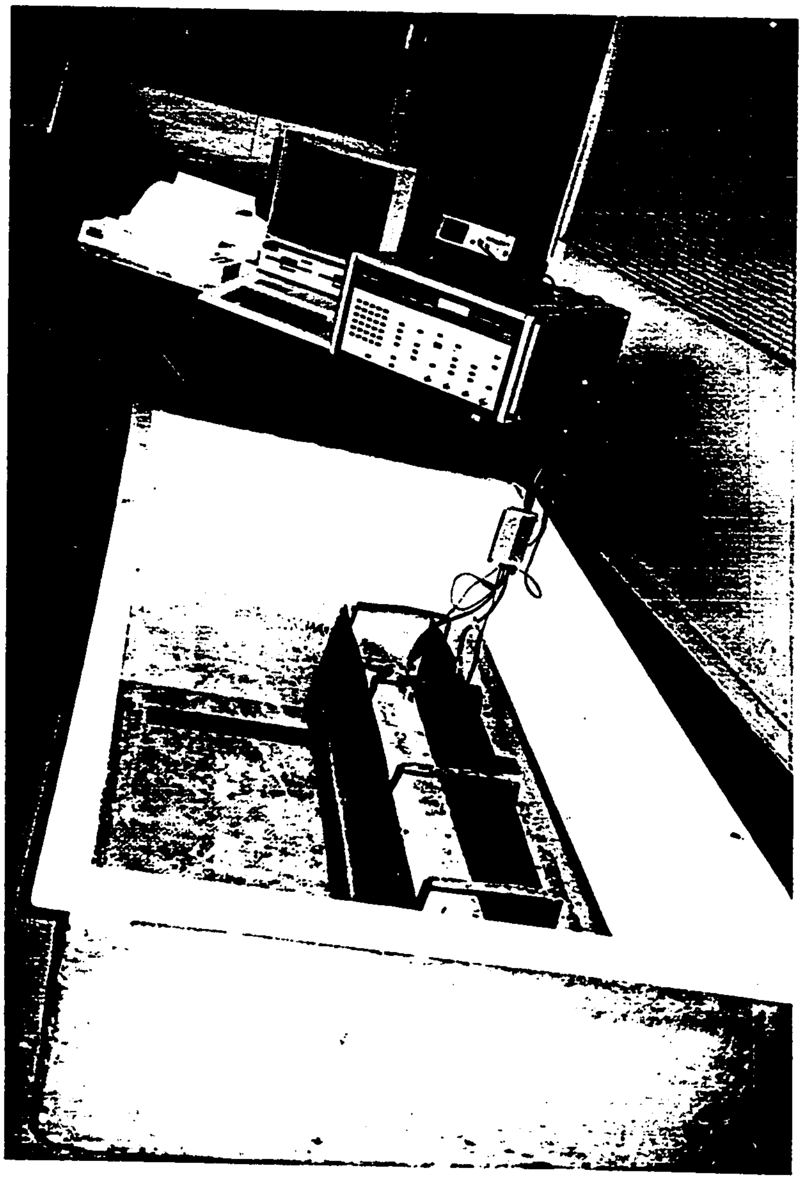


Plate 3.11 Corrosion Rate Measurement Set-up.

electrode which can be another steel bar serves as a cathode. The change in the slope of the current-time plot indicates initiation of cracking due to rebar corrosion.

In this investigation prismatic samples measuring 62.5 x 100 x 300 mm with a centrally placed 12 mm diameter reinforcing bar were cast. The steel bar had a concrete cover of 25 mm at the bottom (Plate 3 .12). The steel bars were cleaned thoroughly using silicon carbide paper and degreased before casting. Three samples were cast from each repair material. Concrete samples containing silica fume as a 10% replacement of cement were also cast in this series. After casting, the specimens were covered with wet burlap for 24 hours prior to demolding. After demolding, steel bars outside the concrete were painted with spray paint in order to prevent corrosion and then the samples were cured in potable water for 28 days.

At the end of the curing period, each sample was placed in a tank containing 5% sodium chloride solution separatly. The level of the solution was adjusted so that two thirds of the depth of the sample was in the solution. A stainless steel frame was used as a counter electrode, and a Standard Calomel Electrode (SCE) was used as a reference electrode (Plate 3.13). Figure 3.4 is a schematic representation of the test set-up. The steel bar was corroded by impressing a potential of + 4V against SCE using EG&G PAR Model 363 Potentiostat/Galvanostat. The resulting current between the counter and working electrode was recorded using a Data logger. The current readings was recorded at programed intervals of time

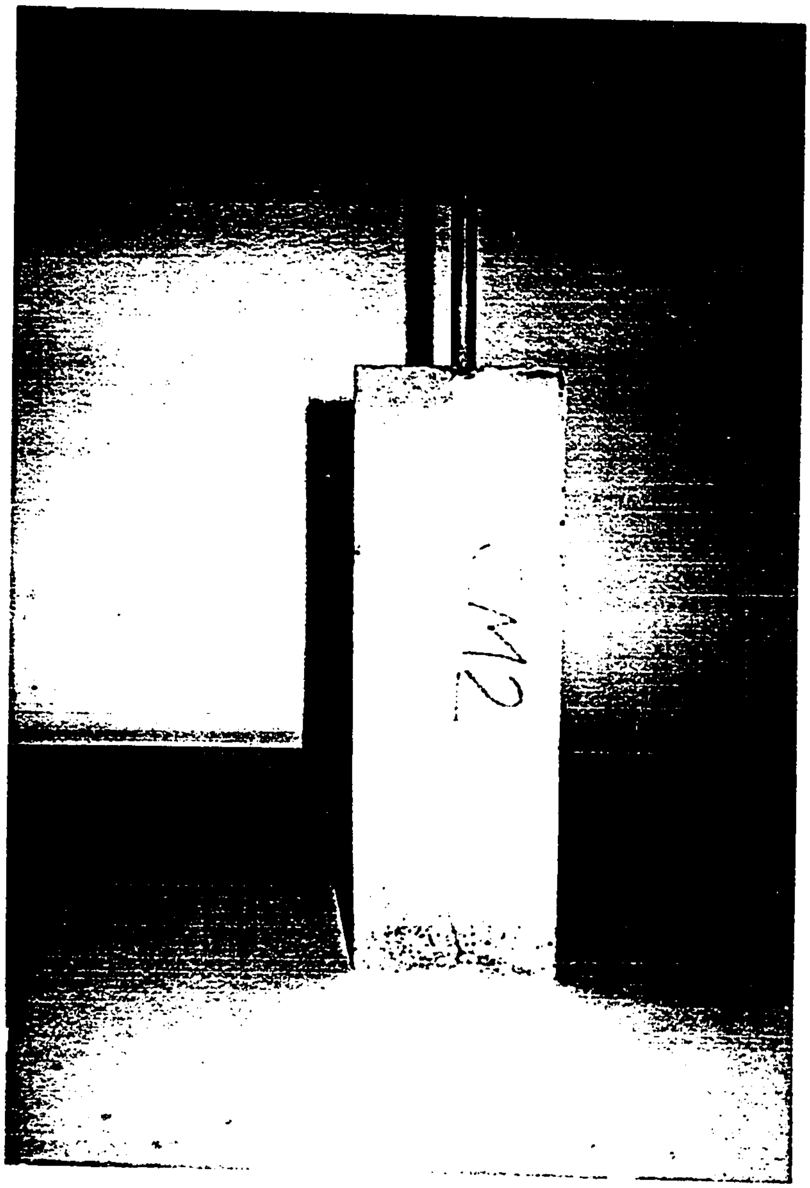


Plate 3.12 Samples for Impressed Current Test.

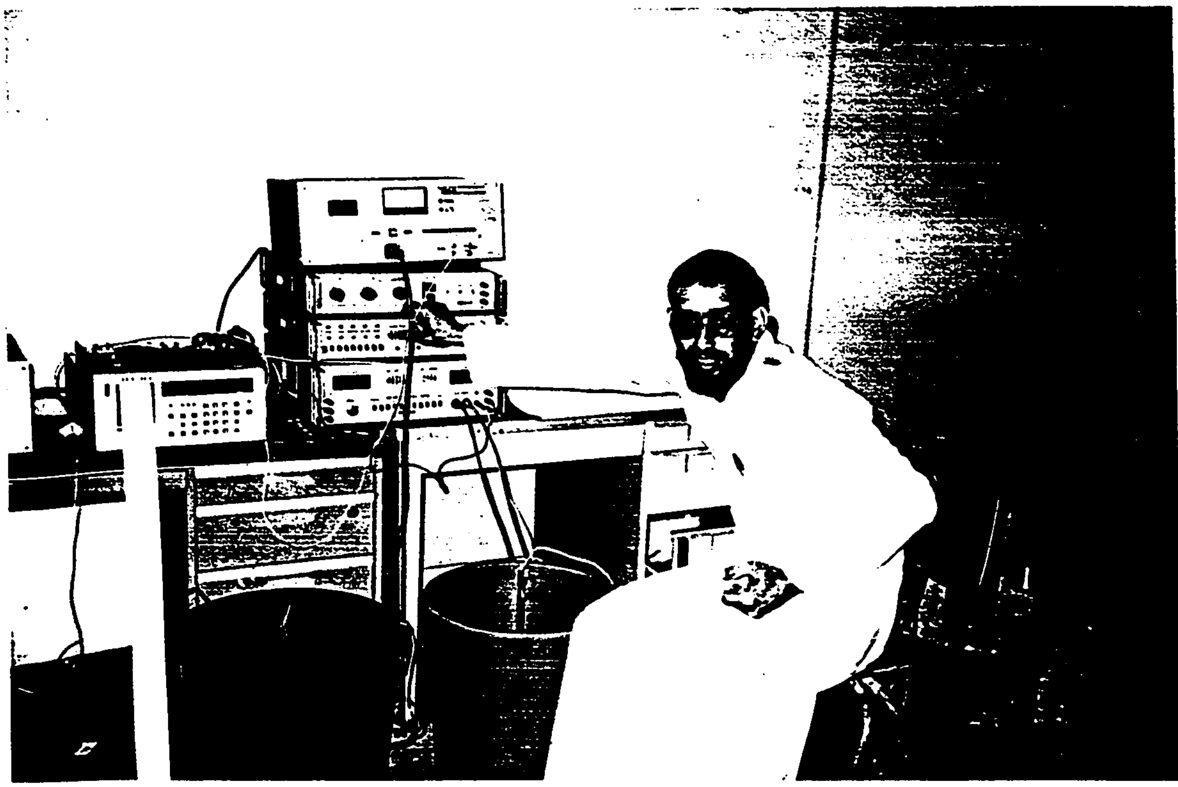


Plate 3.13 Impressed Current Test Set-up.

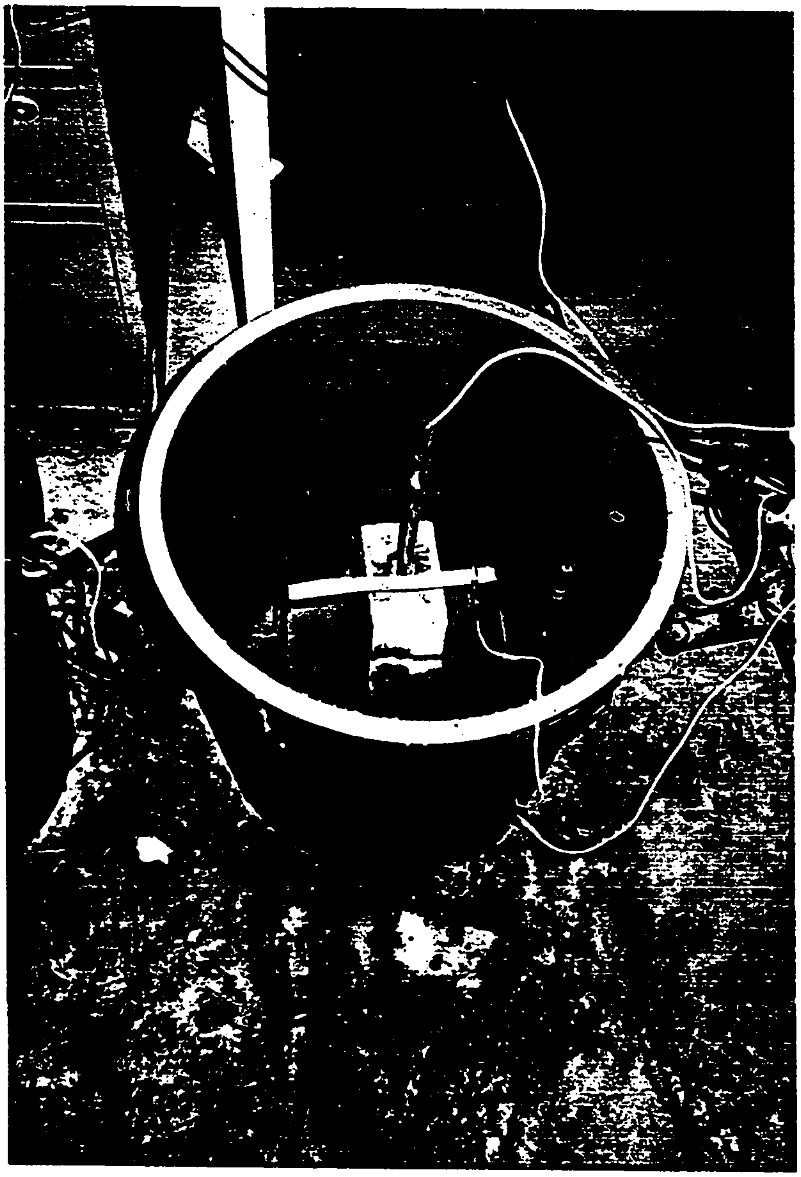


Plate 3.14 Detail of Connection in the Impressed Current Test

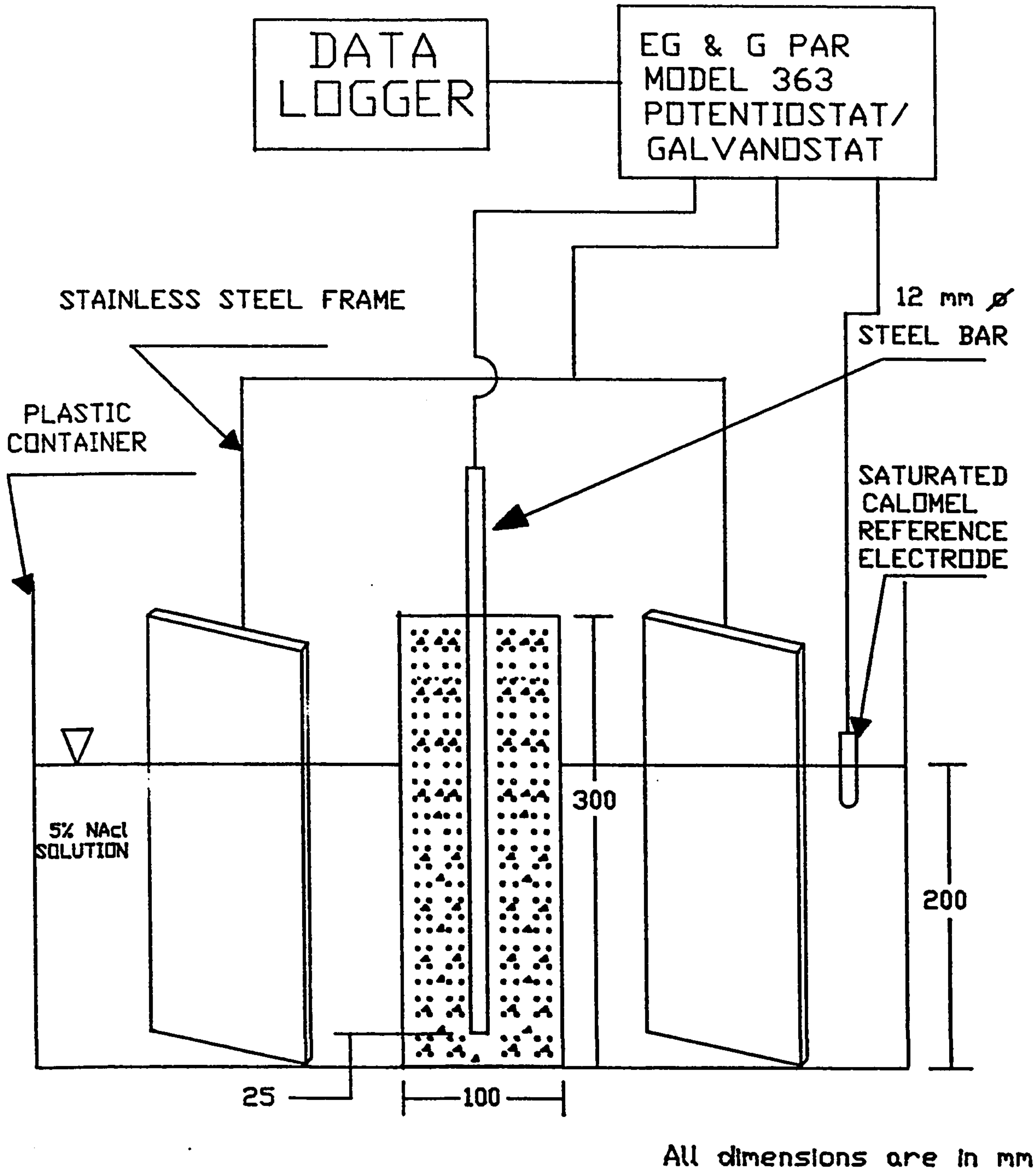


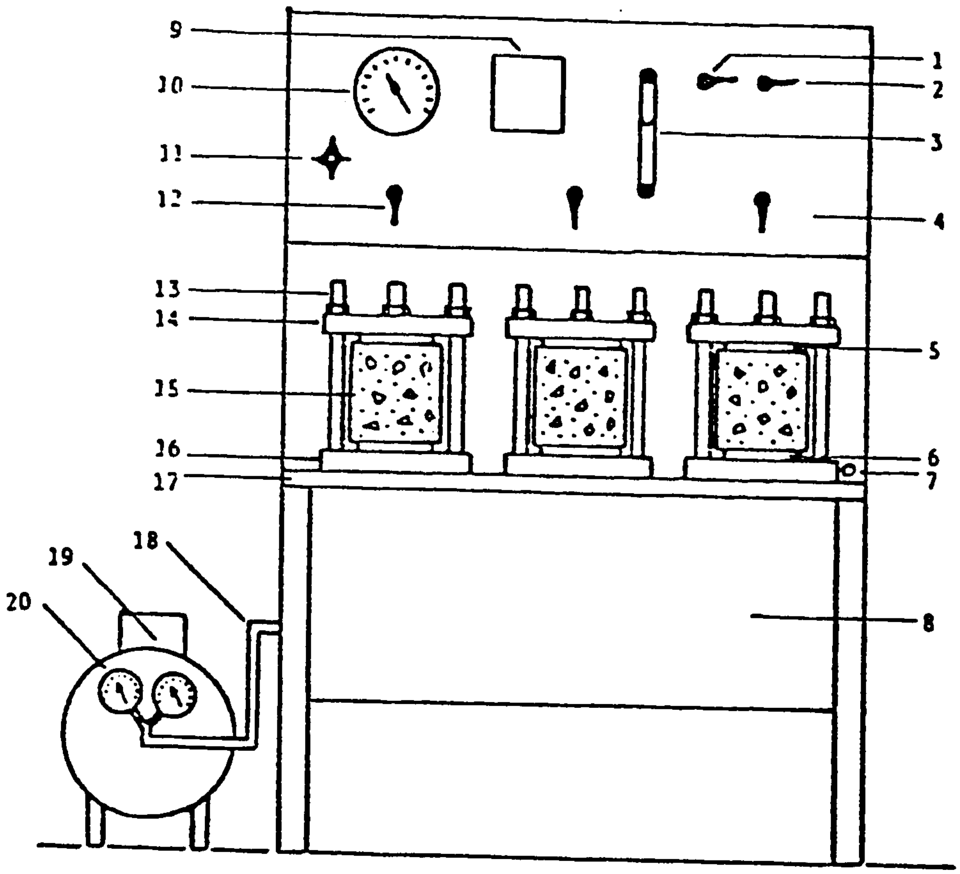
Figure 3.4 Experimental Set-up for Impressed Current Testing

and then the current readings were plotted against time. The point of change in the slope of the current-time record is an indication of the initiation of rebar corrosion.

3.4 Water Permeability Test

Water permeability test was performed according to German Standards DIN 1048. using "Water Impermeability Tester" as shown in Plate 3.15 . In this test, water is applied on a concrete specimen under a pressure of one bar. This pressure is maintained for a period of 48 hours, after which it is increased to 3 bars and maintained for 24 hours, finally the pressure is increased to 7 bars for another 24 hours. At the completion of the test, the specimens are taken out and split open using a compression machine as shown in Plate 3.16. The water penetration profile on the surface of the concrete is recorded and the maximum depth of water penetration is determined from this profile as the water permeability of that sample. Specimens 150 x 150 x 150 mm were cast from the various repair materials for testing the water impermeability. Figure 3.5 shows a Schematic representation of the test set-up.

The effect of heat cool cycling on the water permeability was also investigated. Specimens from the various repair materials (Ordinary cement mortar, ferrocement mortar, polymer modified cementitious mortar and silica fume mortar) in addition to plain concrete specimens were subjected to heat-cool cycling using the same procedure as outlined in Section 3.2.3 for beams. The samples were divided into five groups (Plate 3.9). The samples in the first through the fifth group were subjected to 0,



(1) Water Supply Valve
(2) Water Overflow Valve
(3) Water Level Column
(4) Control Panel
(5) Top Rubber Gasket
(6) Bottom Rubber Gasket
(7) Overflow Outlet
(8) Pipe and Hose Cabinet
(9) Valve Instruction Panel
(10) Pressure Dial Gage
(11) Pressure Adjustment Tap
(12) Compartment Water Valve
(13) Anchoring Nut and Thread
(14) Top Triangular Steel Plate
(15) Concrete Cube Specimen
(16) Bottom Triangular Steel Plate
(17) Permeability Machine Table
(18) High Air Pressure Hose
(19) Air Compressor Unit
(20) Compressor Pressure Dial Gages

Figure 3.5 : Schematic Diagram for Water Permeability Test Setup

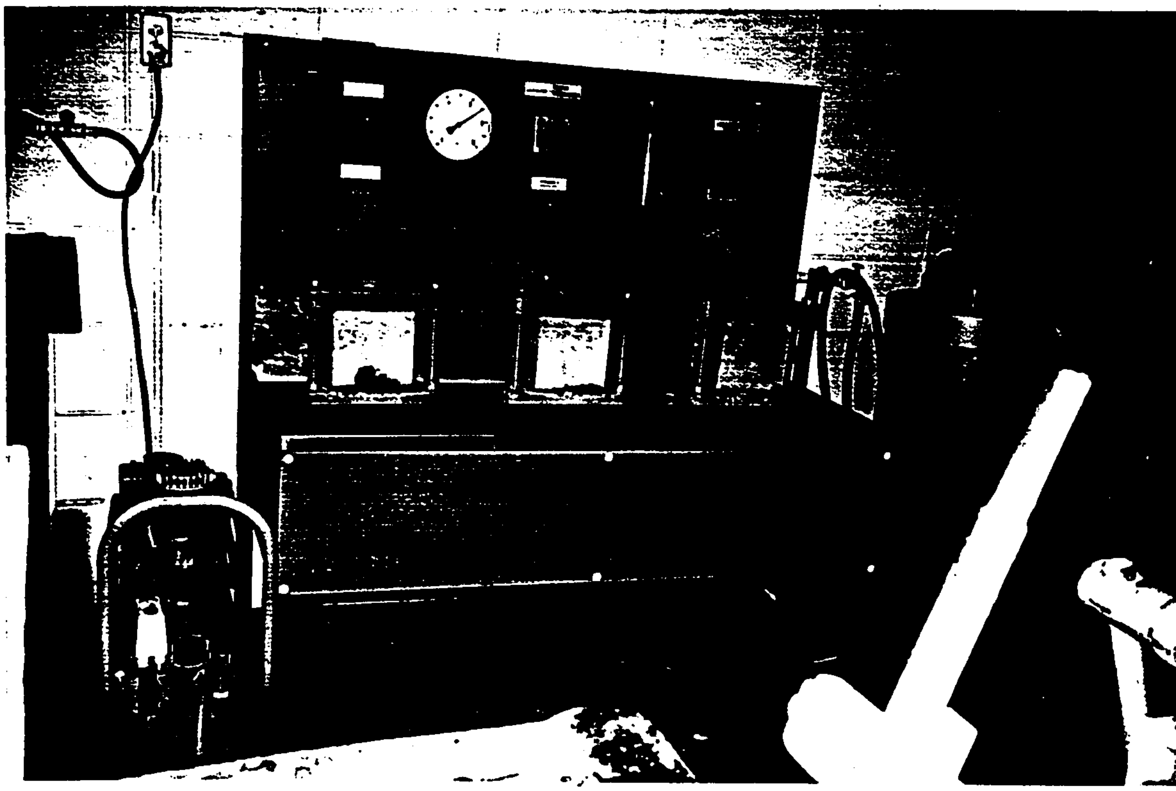


Plate 3.15 Impermeability Tester Machine.

Plate 3.16 Spliting of Samples to Determine the Water Penetration Depth

10, 30, 60, and 120 thermal cycles respectively. The permeability of these groups of samples was compared with control samples (plain concrete).

3.5 Chloride Permeability

Accelerated chloride ion diffusion under application of external electric field which is called chloride permeability test or accelerated electro-osmosis test was performed in this investigation. This test, which was originally developed by David Whiting at the Portland Cement Association (PCA) was later adopted by the American Association of Highway Transportation Officials (AASHTO) as AASHTO Standard T 277, evaluates the performance of various materials based on the diffusion of chloride ion in these materials. In this test the specimen is clamped between the two halves of a chloride permeability cell. One half portion of the cell contains a reservoir which is filled with 3% sodium chloride solution. This portion is connected to the negative terminal of a DC power source. The second half of the cell is filled with 0.3 N sodium hydroxide solution, and is connected to the positive terminal of the power source. One copper mesh is provided on each side of the cell for impressing current on the specimen. Three concrete specimens, 75 x 150 mm cylinders were cast using the various repair materials in addition to plain concrete. These specimens were cured for 28 days. after 60 days three specimens for each category were cut to 75 x 51 mm slices for chloride permeability determination. The curved surface of the slices were coated with a rapid set epoxy. The samples were then saturated with water, under vacuum as per the procedures outlined in the standard. The samples were then fixed in the permeability cell. Rubber shims were used to prevent leakage.

A Hewlett-Packard D.C. power supply equipment was used to apply a potential of 60 V. The intensity of the current flowing across the sample was determined using a resistor connected with the power line. The potential and current data were recorded using a data logger. The experiment was conducted for 6 hours.

The current was plotted against time. The area under the curve is the total charge passed in Coloumbs (ampere-seconds). Higher value of the total charge indicates increased diffusion of chloride ions. Three samples from each group were tested. Plate 3.17 shows the experimental set-up and Figure 3.6 is a schematic representation of the chloride permeability test.

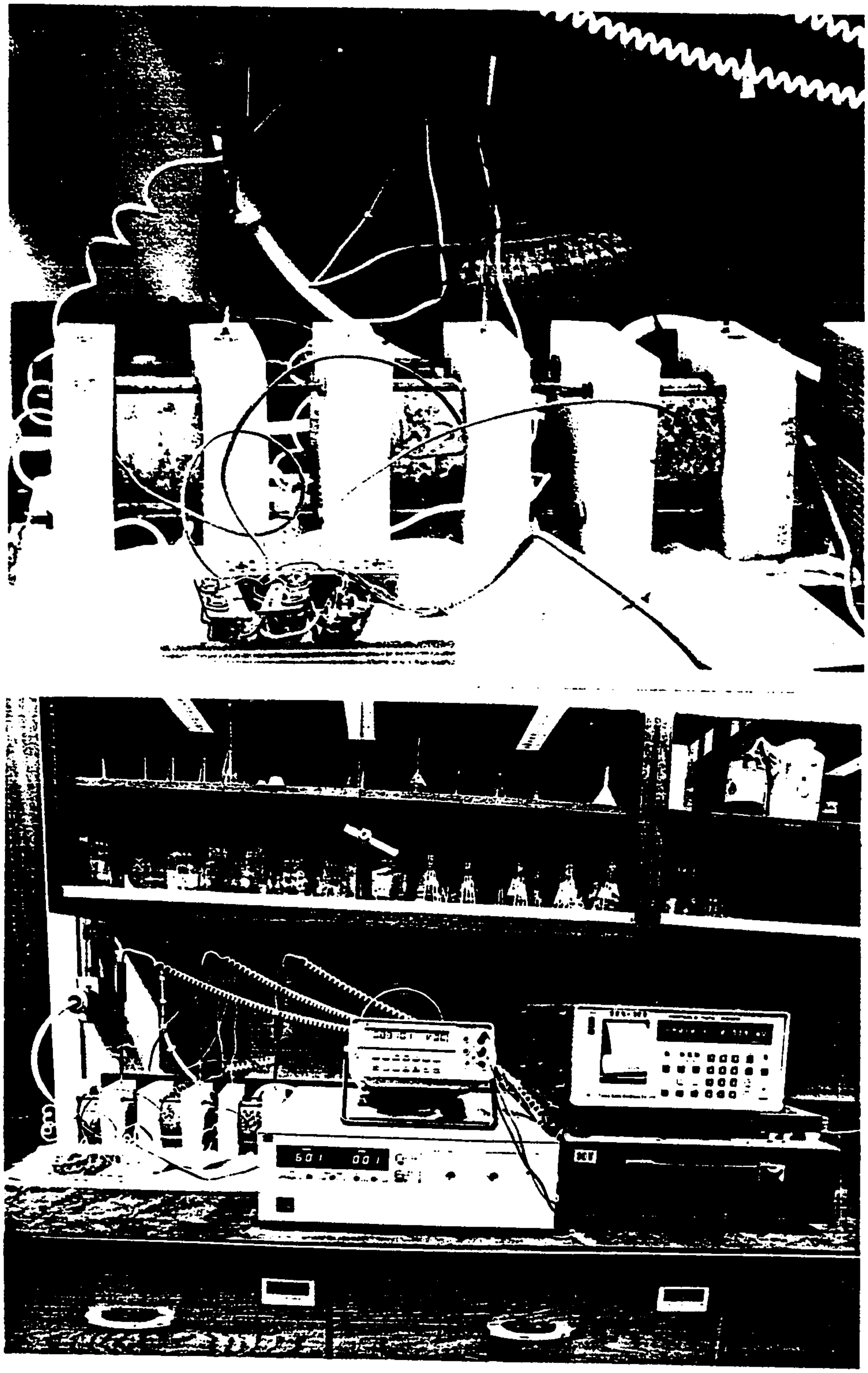


Plate 3.17 Chloride Permeability Test Set-up.

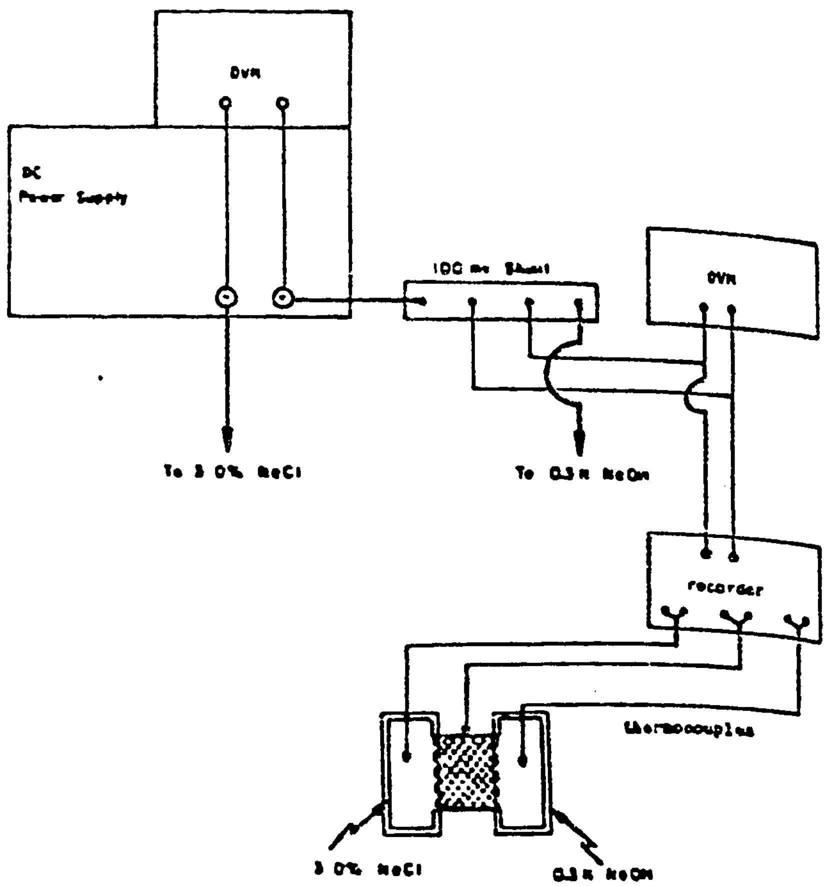


Figure 3.6 : Schematic Diagram for Chloride Permeability Test Setup

CHAPTER 4

ANALYSIS OF DATA AND DISCUSSION OF RESULTS

This chapter deals with analysis of results obtained in this investigation. The results are presented in Tables 4.1 through 4.10, and Figures 4.1 through 4.47. The results related to water permeability, chloride permeability and corrosion resistance of the repair materials and corrosion of reinforcing steel in the repaired beams are discussed in the following paragraphs.

4.1 Corrosion of Reinforcing Steel in the Repaired Beams

Since corrosion of reinforcement is a major cause of deterioration of concrete structures in the Arabian Gulf region, great emphasis was given to the detection of corrosion in the repaired beams. The corrosion rate of steel in the repaired beams were compared with those in the control beams. The corrosion of steel was evaluated by measuring the half-cell potentials, determining corrosion rates using electrochemical techniques and measuring the half-cell potential noise.

4.1.1 Half-Cell Potentials

The half-cell potentials of rebars in all the beams which were partially immersed in 5% Nacl solution were measured at 24 hours interval. These half-cell potentials are plotted against time in Figures 4.1 through 4.21. Figures 4.1 through 4.10 show the half-cell potentials for rebars in beams which were not subjected to thermal cycling. The half-cell potentials of rebars in beams which were subjected to thermal cycling are shown in Figures 4.11 through 4.21.

Figure 4.1 shows the half-cell potentials of rebars in the three control beams (no repair , no thermal cycling). Figure 4.2 shows the average values of the half-cell potentials for the three control beams. Similarly in Figure 4.3 the half-cell potentials for the three beams repaired with ordinary cementitious mortar are plotted against time, while Figure 4.4 shows the average half-cell potential values of this category of samples. Figures 4.5 and 4.6 show the half-cell potentials of rebars in the three beams repaired with ferrocement, and the average values respectively. The half-cell potentials of rebars in the three beams repaired with polymer modified cementitious mortar are shown in Figure 4.7 and the average values are shown in Figure 4.8.

For comparison purposes the average half-cell potentials of rebars in repaired and control beams are plotted against time of immersion in the

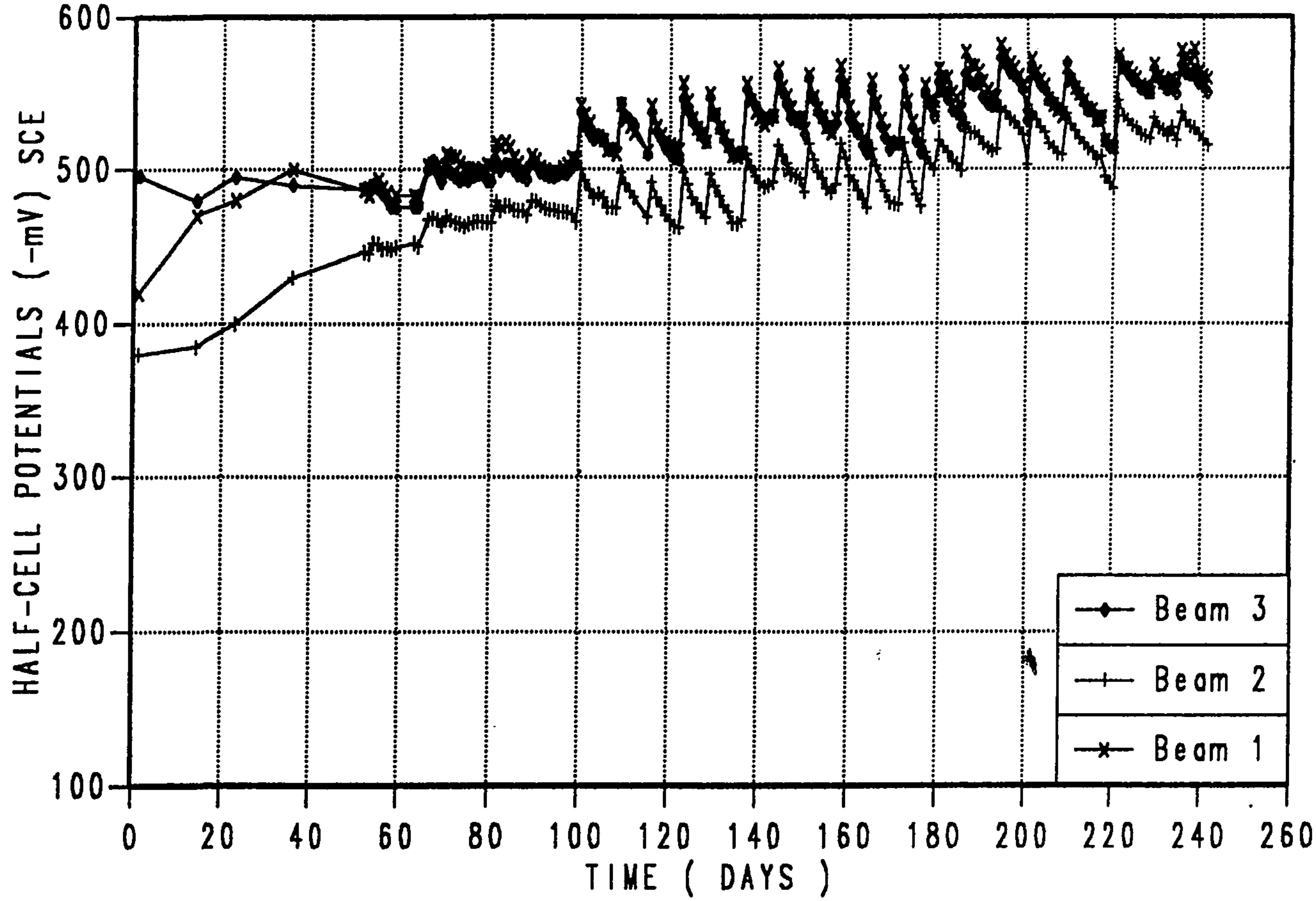


Fig. 4.1: Half-Cell Potential Data for Control Beams

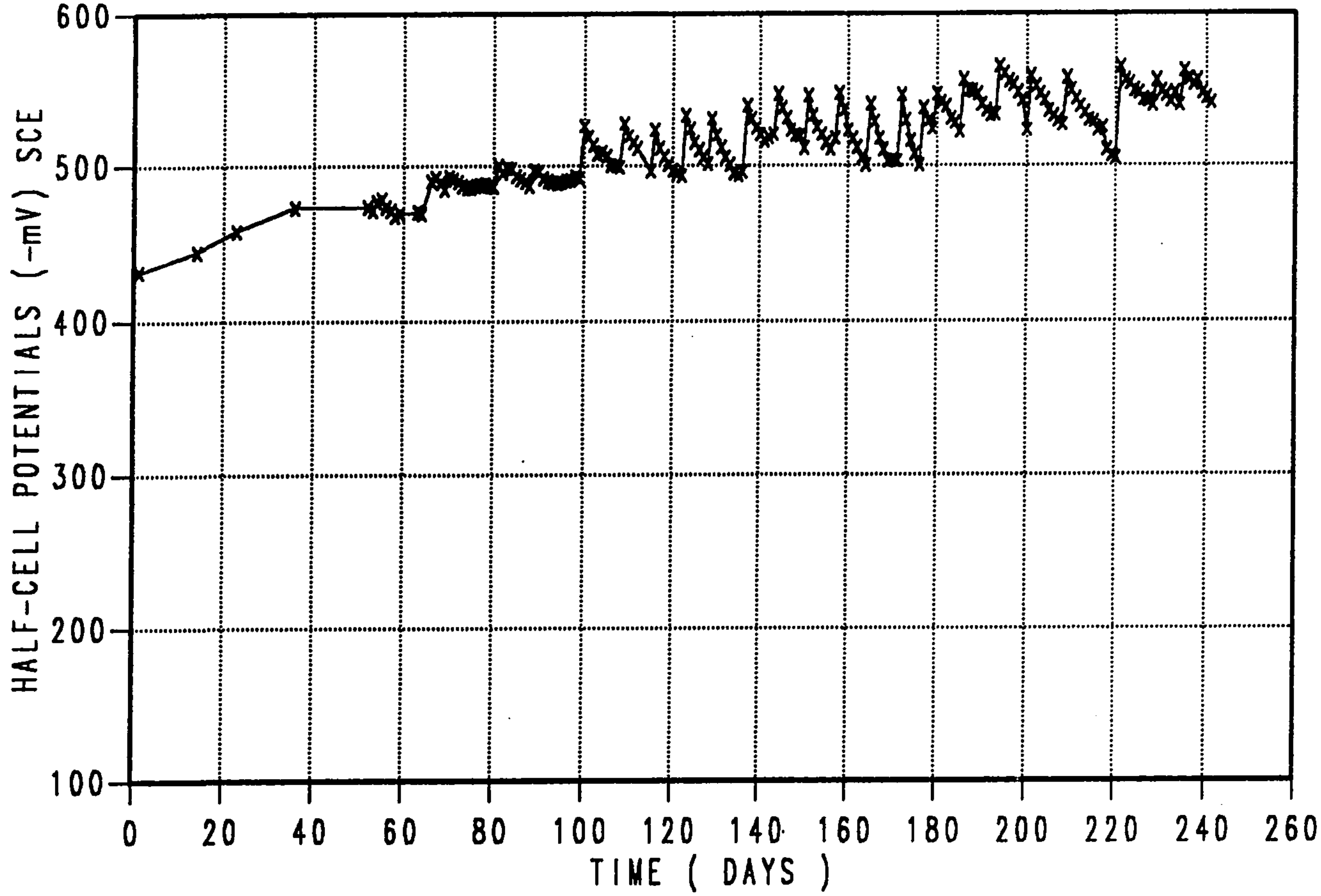


Fig. 4.2: Average Half-Cell Potentials for Control Beams

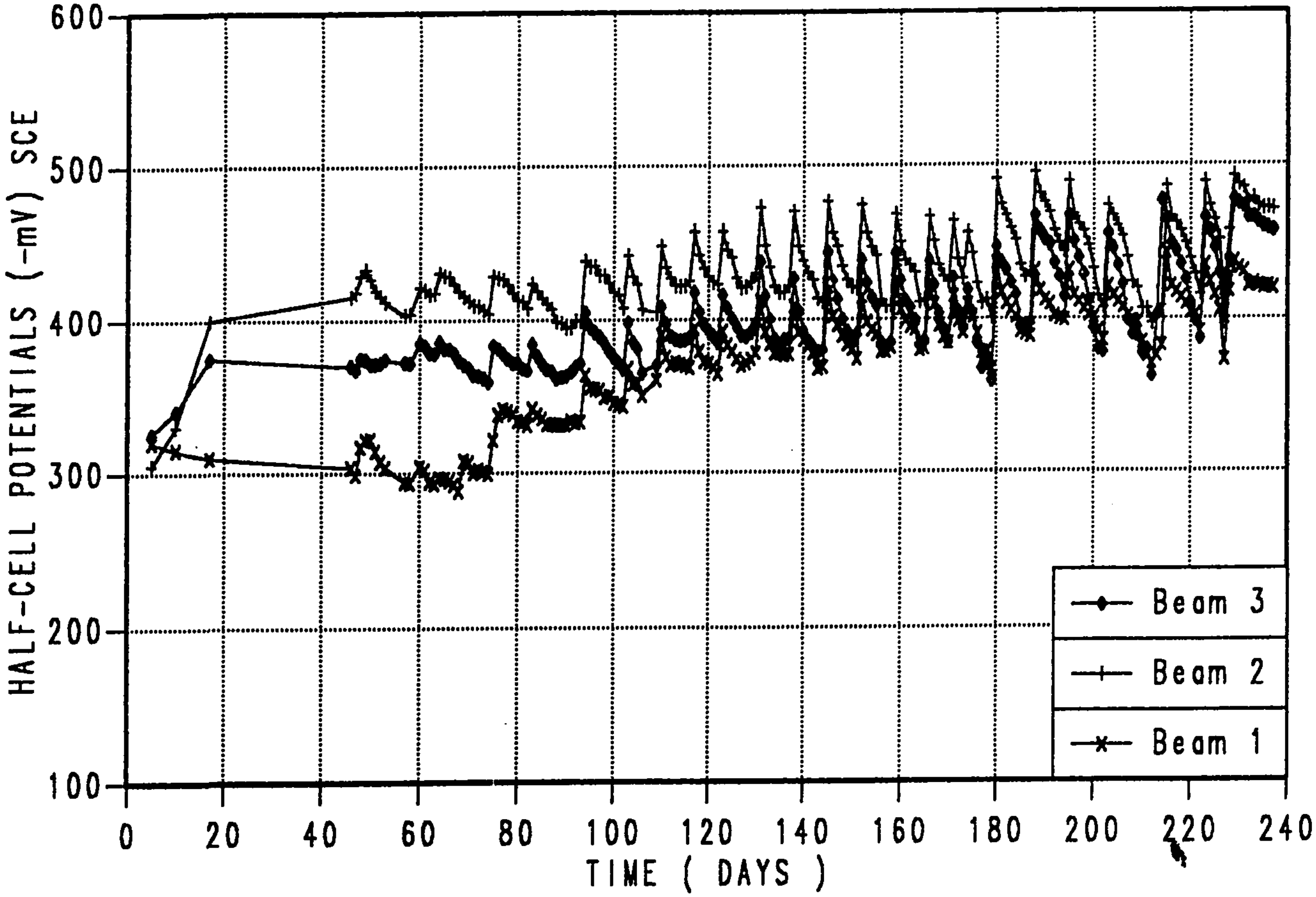


Fig. 4.3 Half-Cell Potential Data for Beams Repaired with Ordinary Mortar

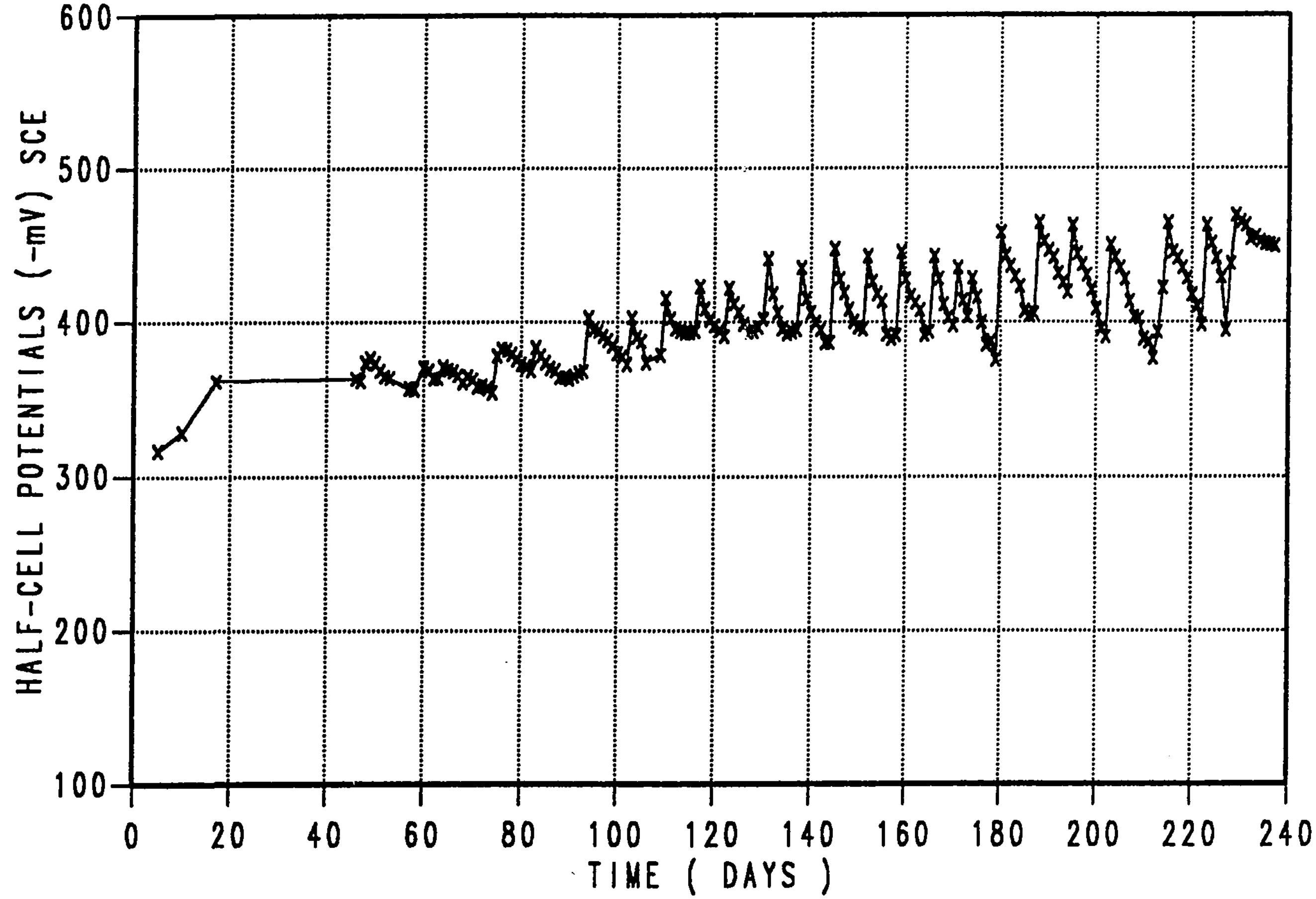


Fig. 4.4: Average Half-Cell Potentials For Beams Repaired with Ordinary Morar

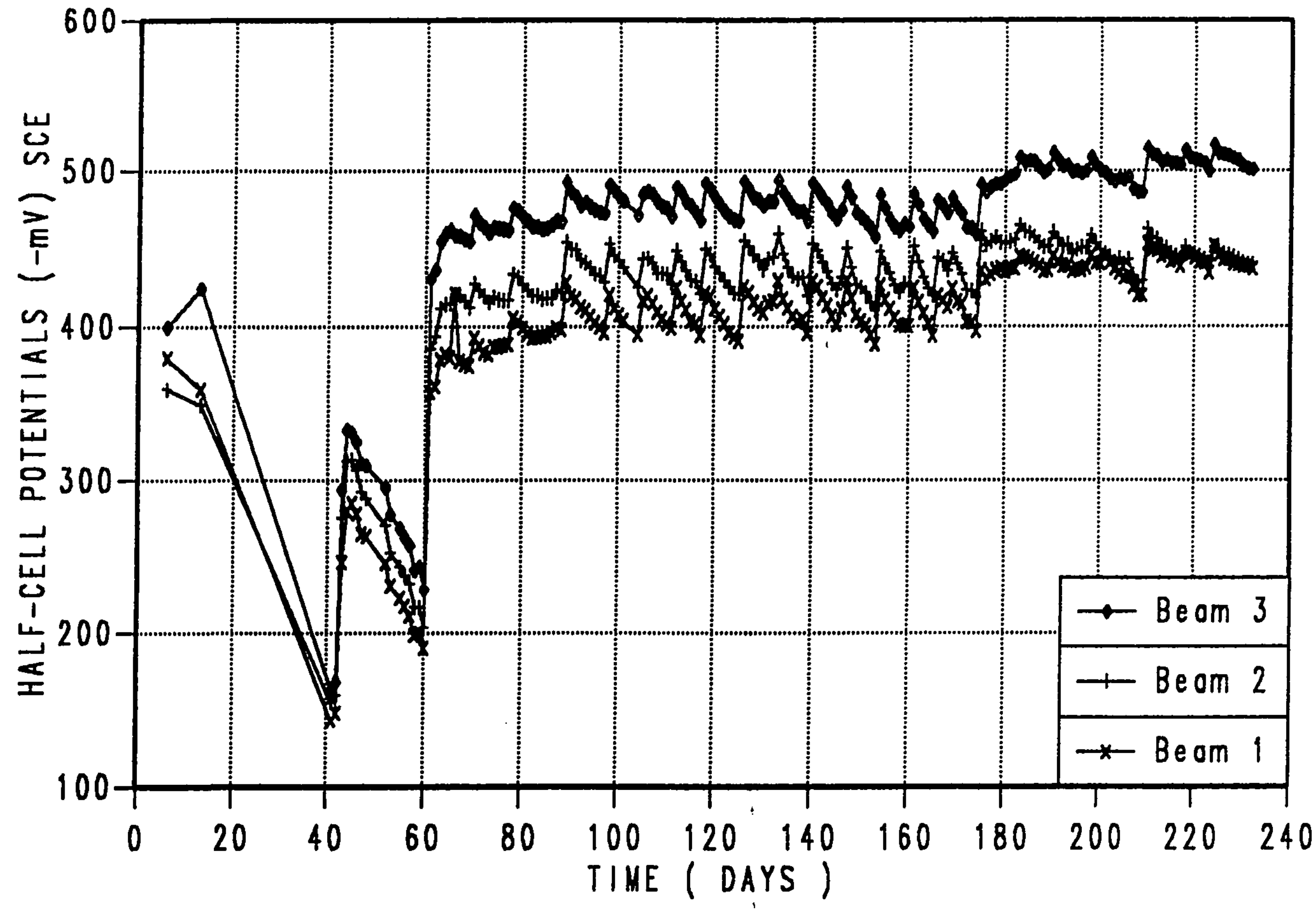


Fig. 4.5: Half-Cell Potential Data for Beams Repaired with Ferrocemnt Mortar

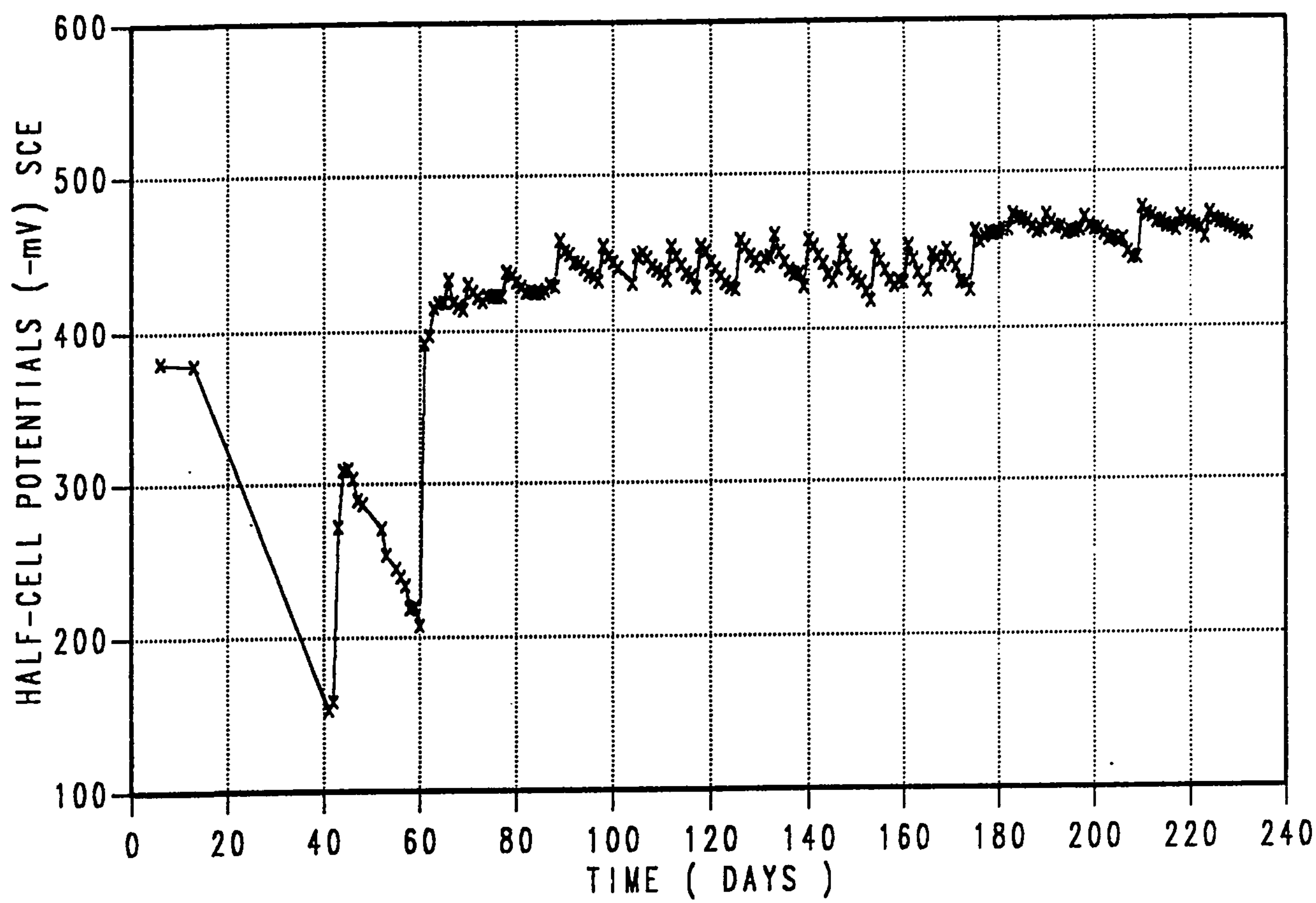


Fig. 4.6: Average Half-Cell Potentials for Beams Repaired with Ferrocement

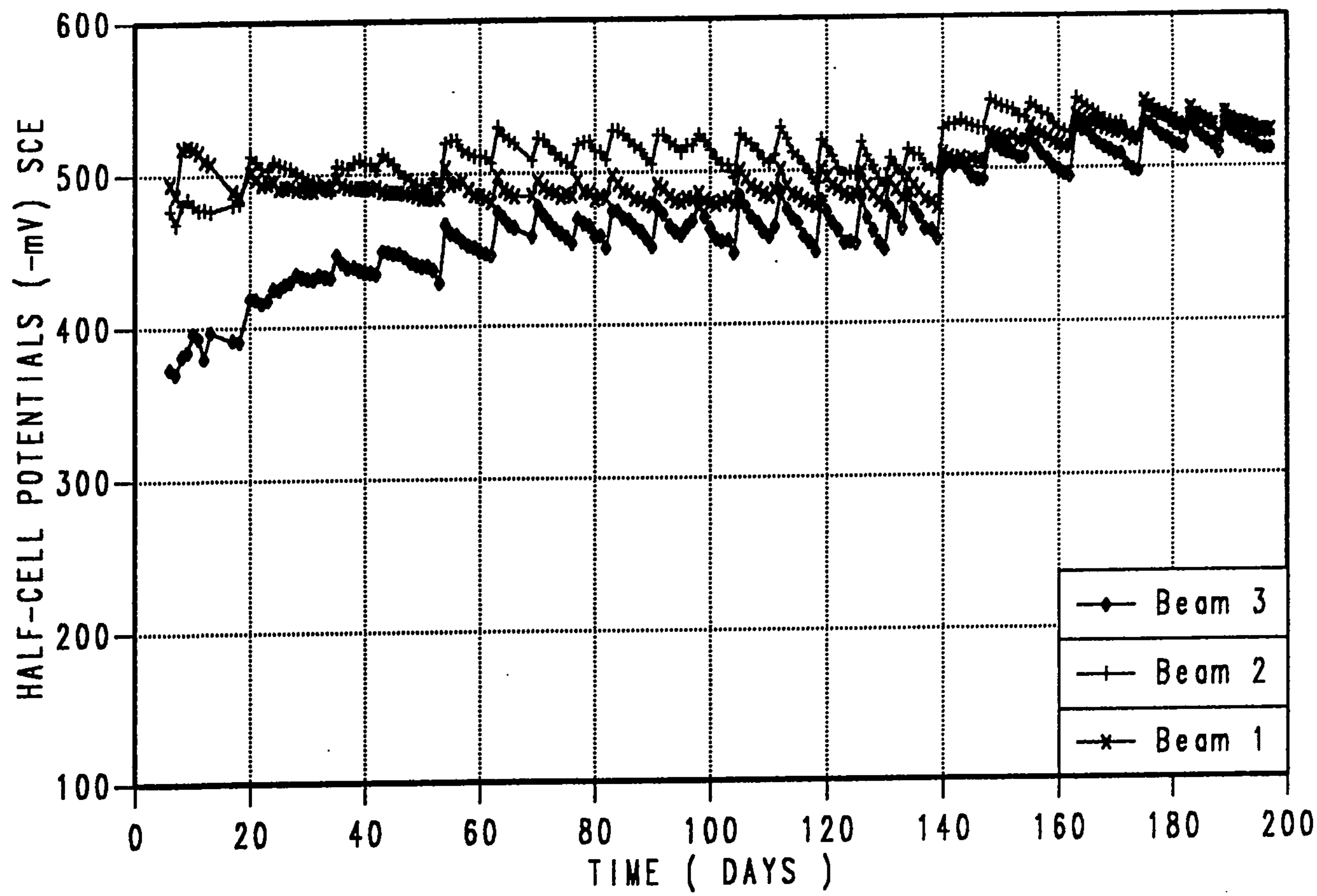


Fig. 4.7: Half-Cell Potential Data for Beams Repaired with Polymer Cement Mortar

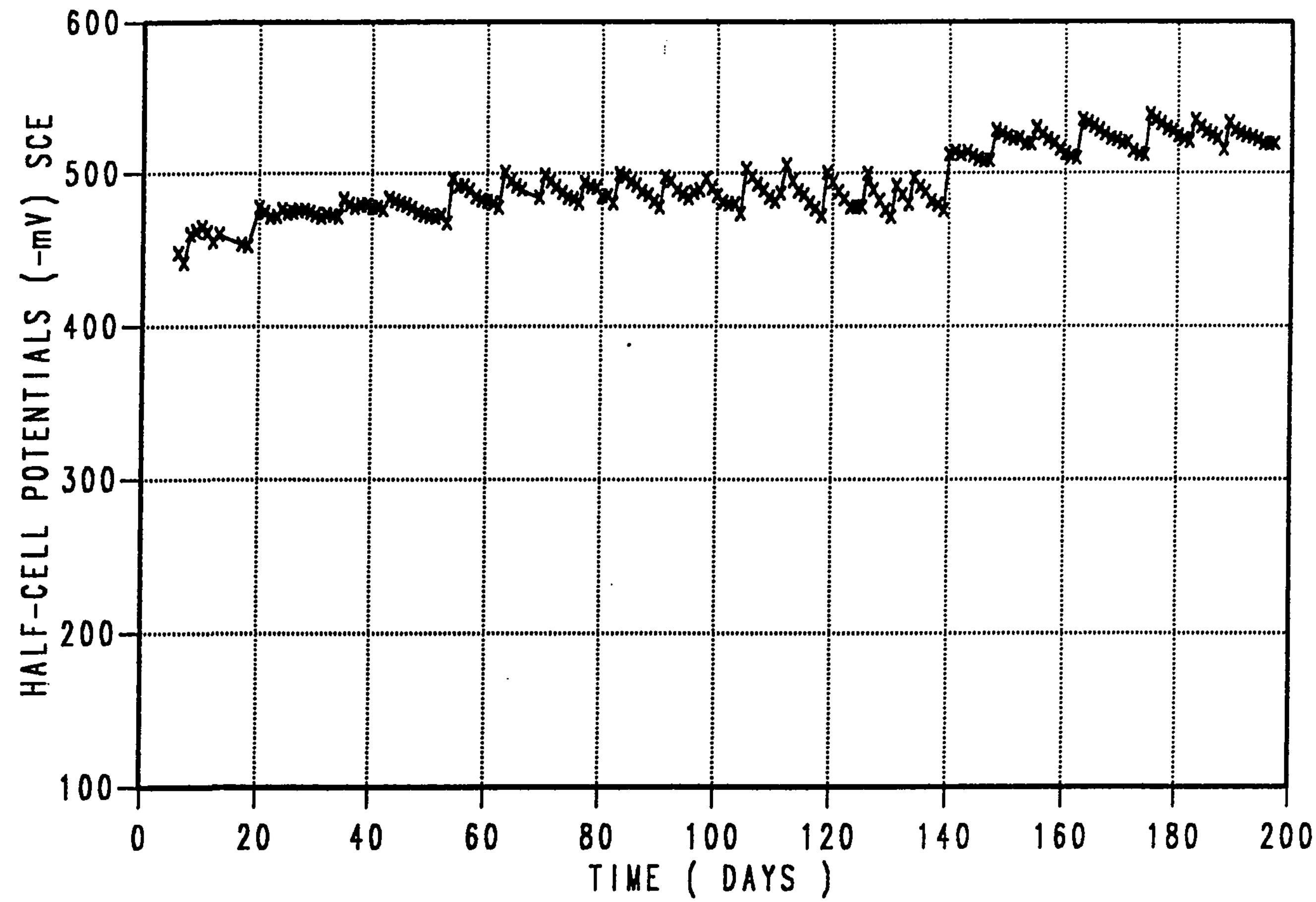


Fig. 4.8: Average Half-Cell Potentials for Beams Repaired with Polymer Mortar

sodium chloride solution in Figure 4.9. The average half-cell potential readings after about 4 months (120 days) of exposure to sodium chloride solution are shown in Figure 4.10.

The half-cell potentials of rebars in the repaired beams are in the range of -400 to -490 mV SCE. The half-cell potentials of rebars in unrepaired beams are about -500 mV SCE. These data indicate that there is a more than 90% probability of active corrosion in both normal and repaired beams according to ASTM C876 criteria.

The half-cell potentials of rebars in beams repaired with ordinary cement mortar and ferrocement mortar were less than in plain concrete. The half-cell potentials of rebars in beams repaired with polymer modified mortar were about the same as those in normal concrete. This apparently indicates that application of polymer to concrete does not retard the ingress of aggressive ions like chlorides. However, it should be remembered that higher half-cell potential values (more negative) do not indicate that the bars are corroded to a higher degree. The more negative values actually dynamically demonstrate that a corrosion mechanism i.e., decrease in ferrous ion concentration to force oxidation of iron, is in operation. That is why ASTM C876 can only state that half-cell measurements more negative than -350 mV Vs Copper-Copper sulfate Electrode (CSE) are 90% certain of demonstrating that corrosion is occuring. In fact of the above, corrosion rate measurements were carried out using electrochemical techniques. The results on corrosion rates of rebars in both repaired and normal concrete are discussed in the following

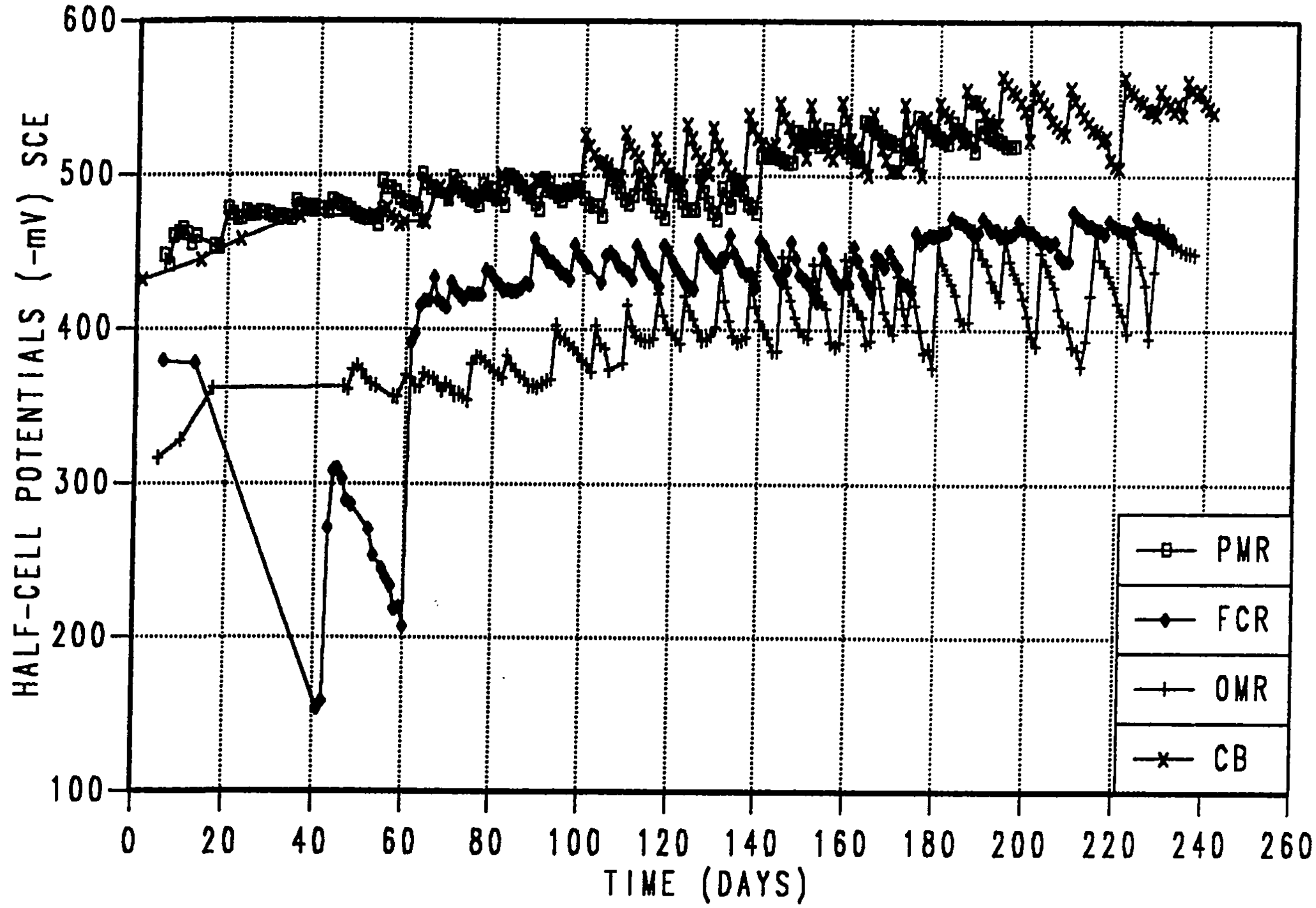


Fig. 4.9: Comparison of Average Half-Cell Potentials for Repaired and Control Beams

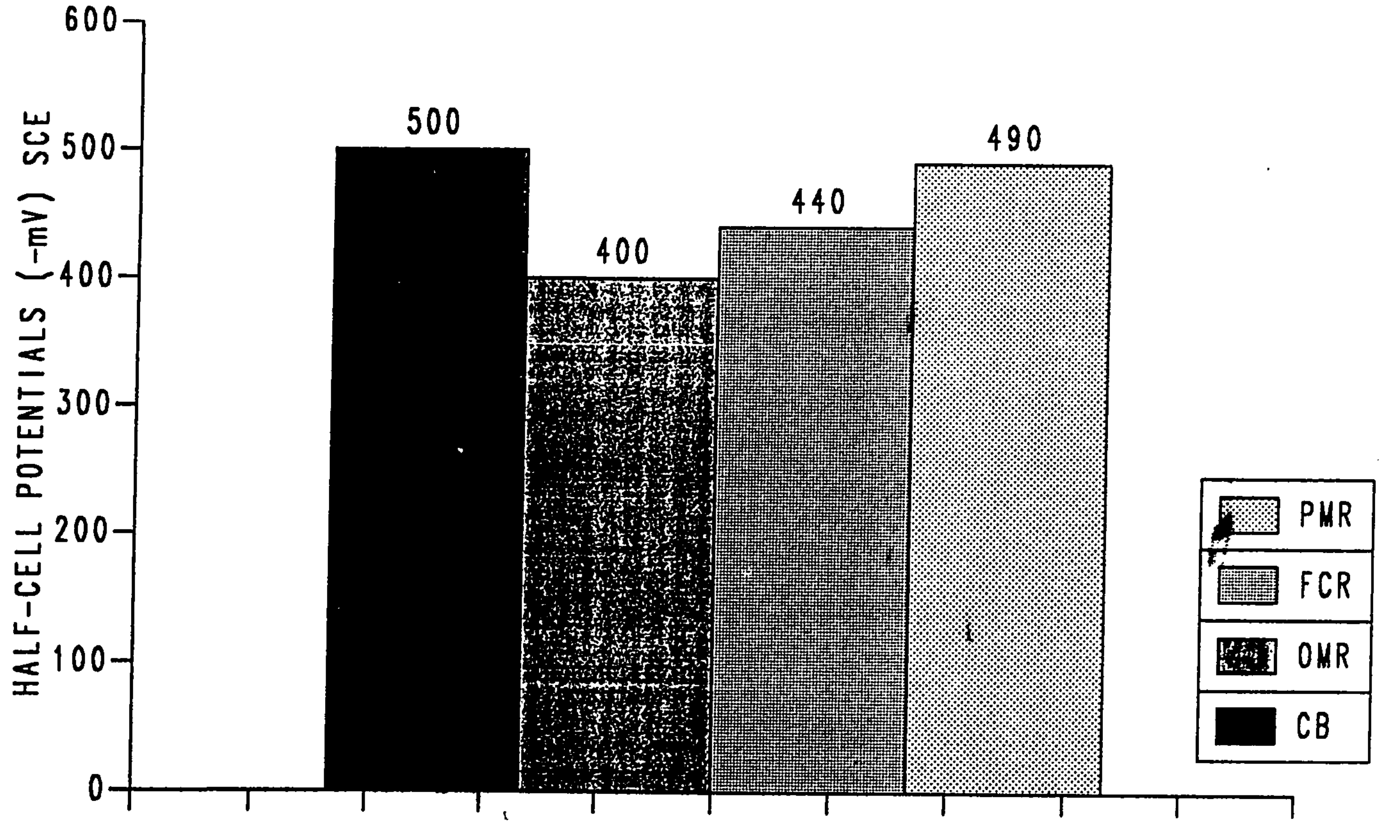


Fig. 4.10: Half-Cell Potentials After 120 Days Exposure to Chlorid Solution for Repaired and Control Beams

paragraphs.

The half-cell potentials of rebars in repaired beams subjected to thermal cycling are shown in Figures 4.11 through 4.21. Figure 4.11 shows the half-cell potential data plotted against time for the beams repaired with ordinary cement mortar and subjected to heat-cool cycles. The average half-cell potential values for these beams are shown in Figure 4.12. Similarly, Figures 4.13 and 4.14 show the half-cell potentials for the three beams repaired with ferrocement mortar and their average values respectively. Figure 4.15 shows half-cell potentials plotted against time for the beams repaired with polymer modified cementitious mortar and subjected to thermal cycling. The average values are shown in Figure 4.16.

The average half-cell potentials of bars in all repaired beams subjected to thermal cycles are compared with the half-cell potentials of rebars in control beams in Figure 4.17. Figure 4.18 shows the half-cell potentials of rebars in repaired beams subjected to thermal cycles, after about 4 months of exposure to sodium chloride solution.

The half-cell potential values of rebars in all the repaired beams subjected to thermal cycling were in the range of -480 to -560 mV SCE. The half-cell potentials of rebars in beams repaired with ordinary mortar and subjected to thermal cycling were lower than the half-cell potentials of rebars in beams repaired with ferrocement and polymer mortar and subjected to thermal cycling. Further, the half-cell potentials of rebars in repaired beams subjected to heat-cool cycling were in active state according to ASTM C876.

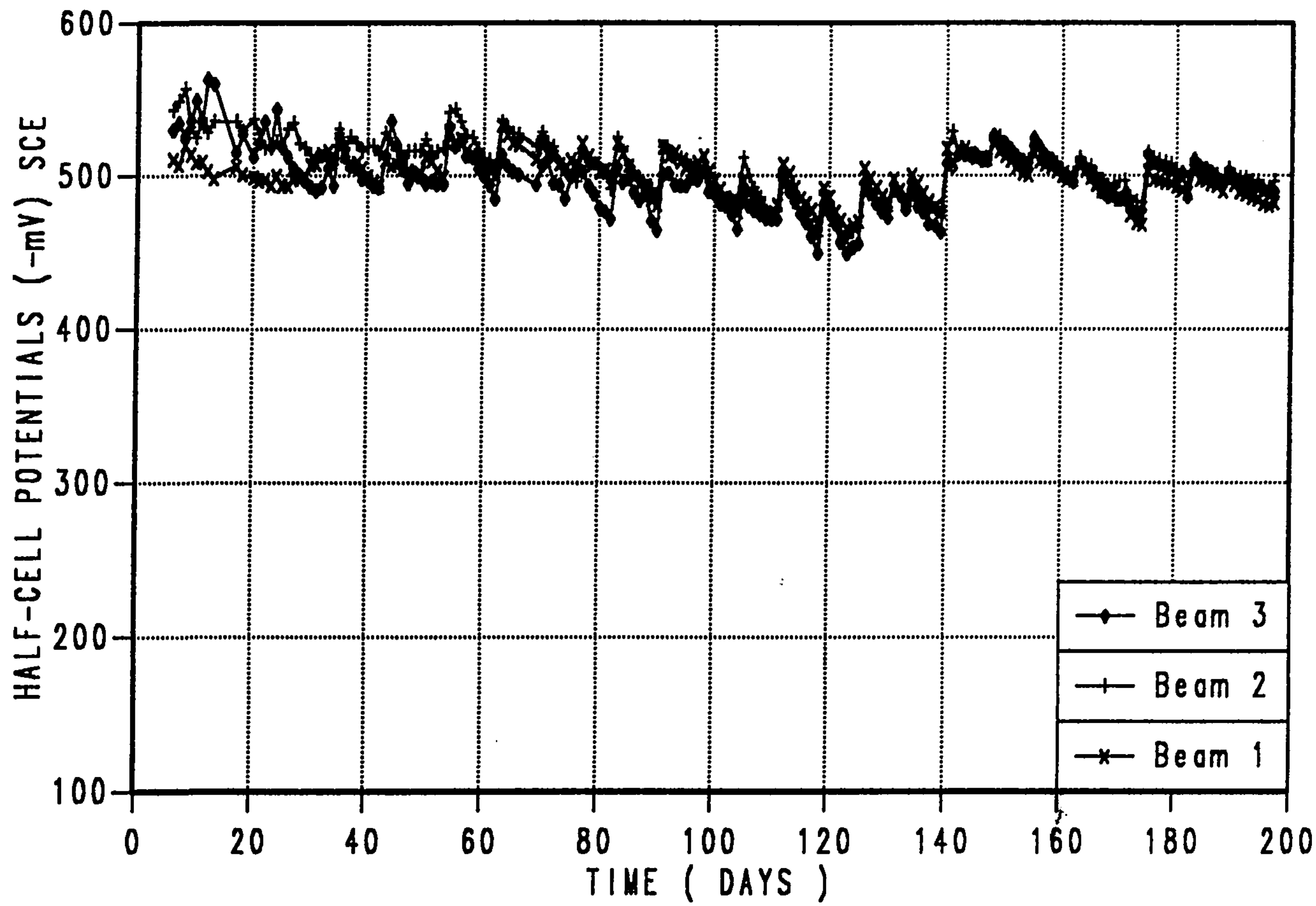


Fig. 4.11 Half-Cell Potential Data for Beams Repaired with Oridnary cement Mortar and Subjected to Thermal Cycling

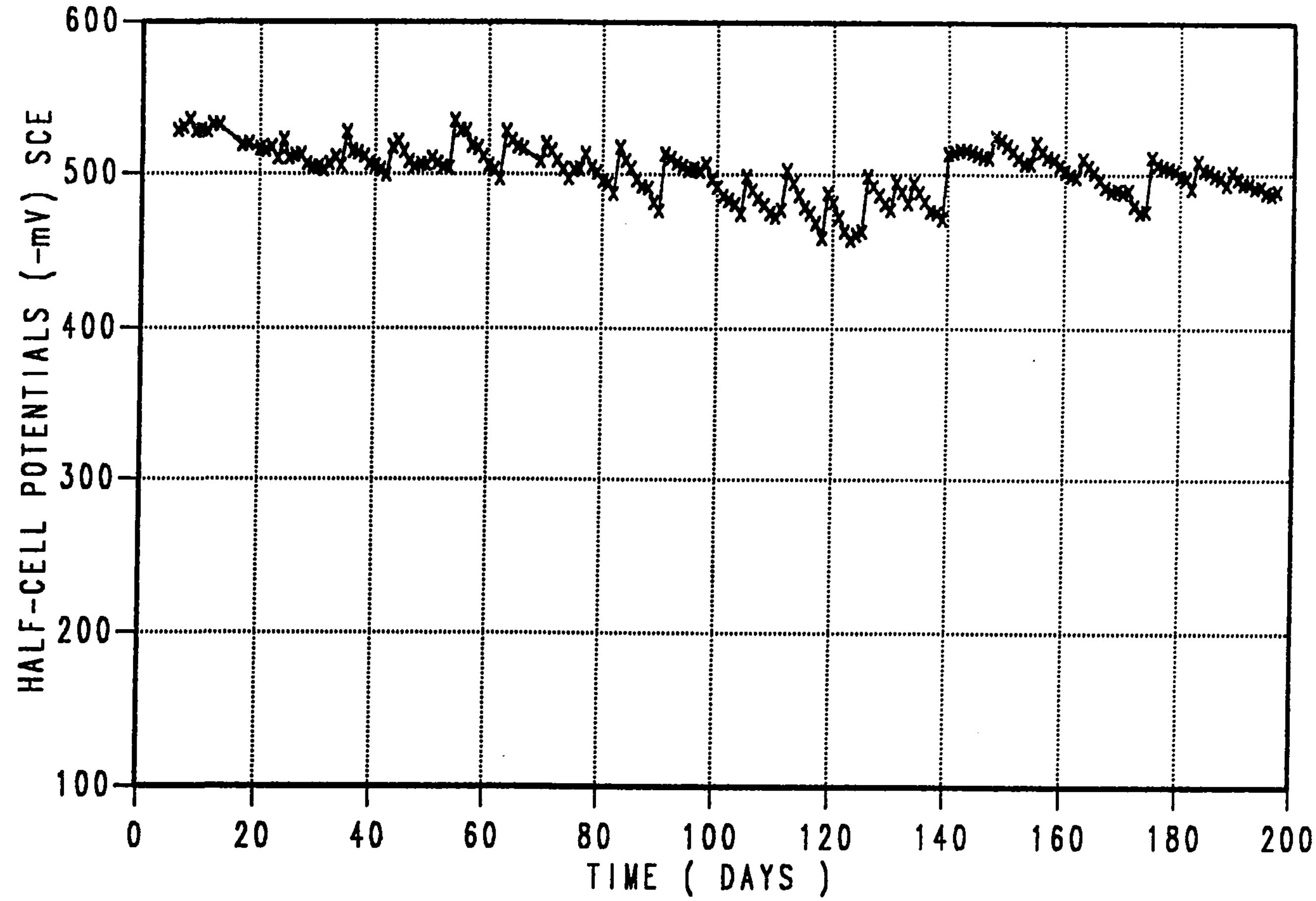


Fig. 4.12: Average Half-Cell Potentials for Beams Repaired with Ordinary Cement Mortar and Subjected to Thermal Cycling

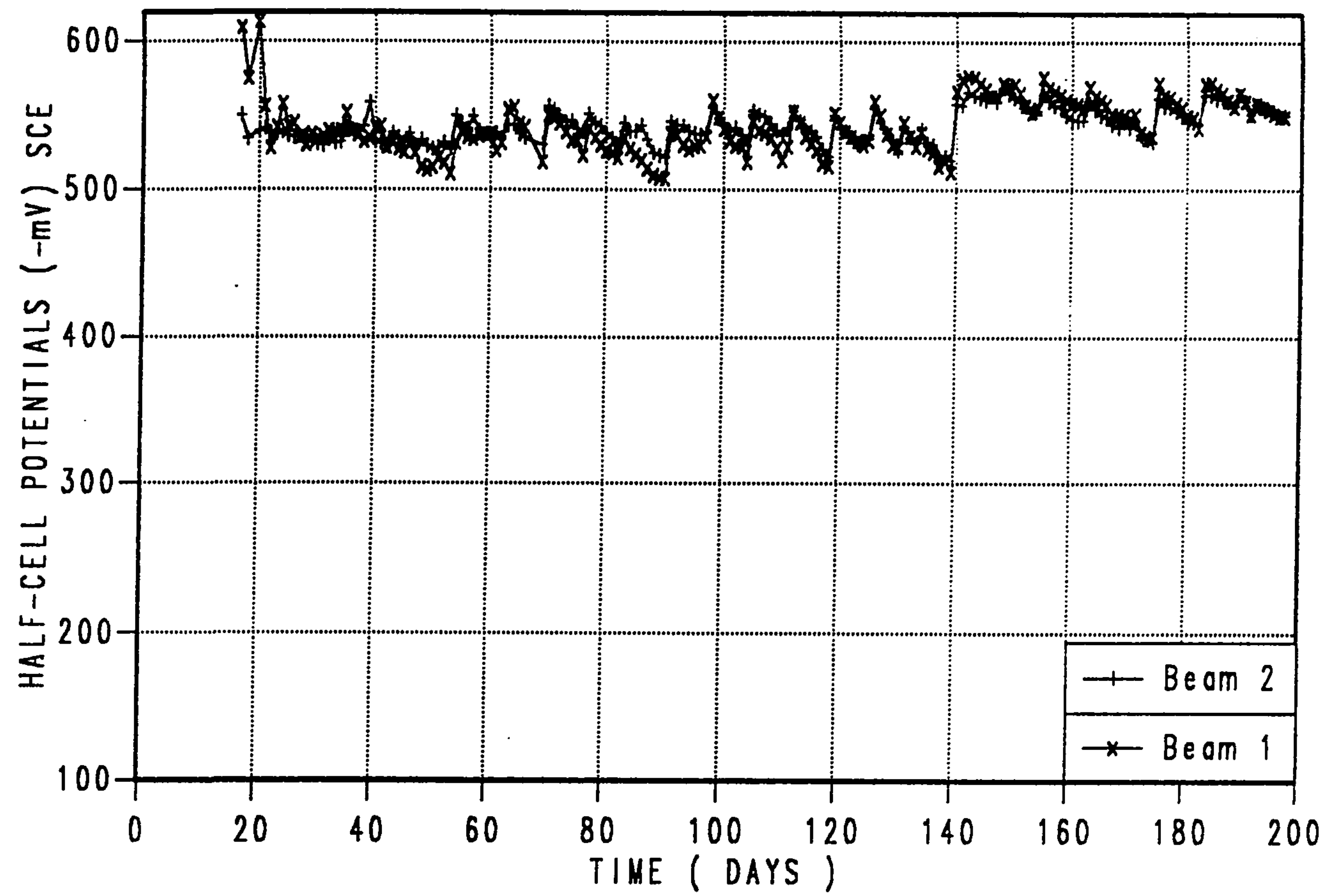


Fig. 4.13 Half-Cell Potential Data for Beams Repaired with Ferrocement Mortar and Subjected to Thermal Cycling

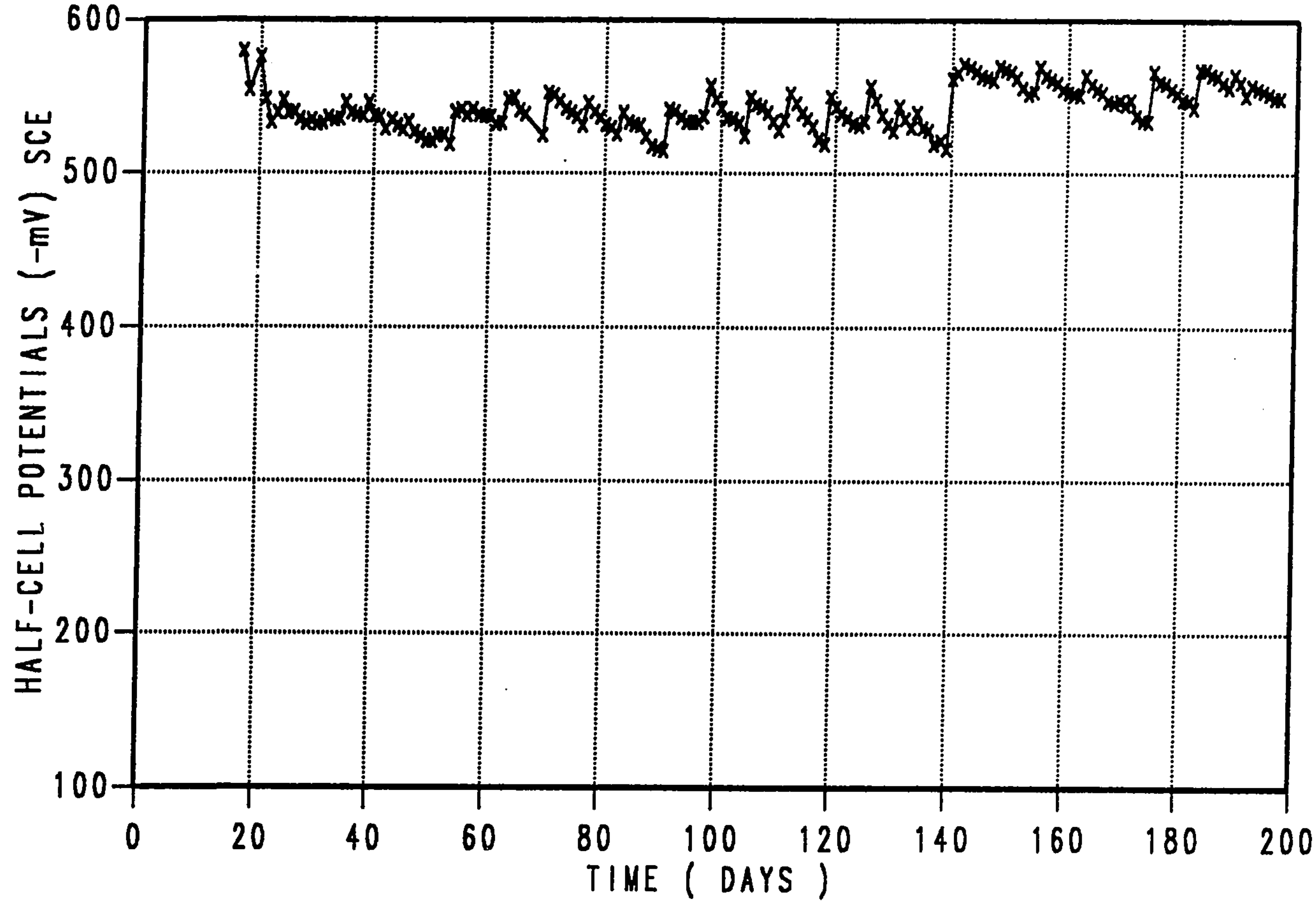


Fig. 4.14: Average Half-Cell Potentials for Beams Repaired with Ferrocement Mortar and Subjected to Thermal Cycling

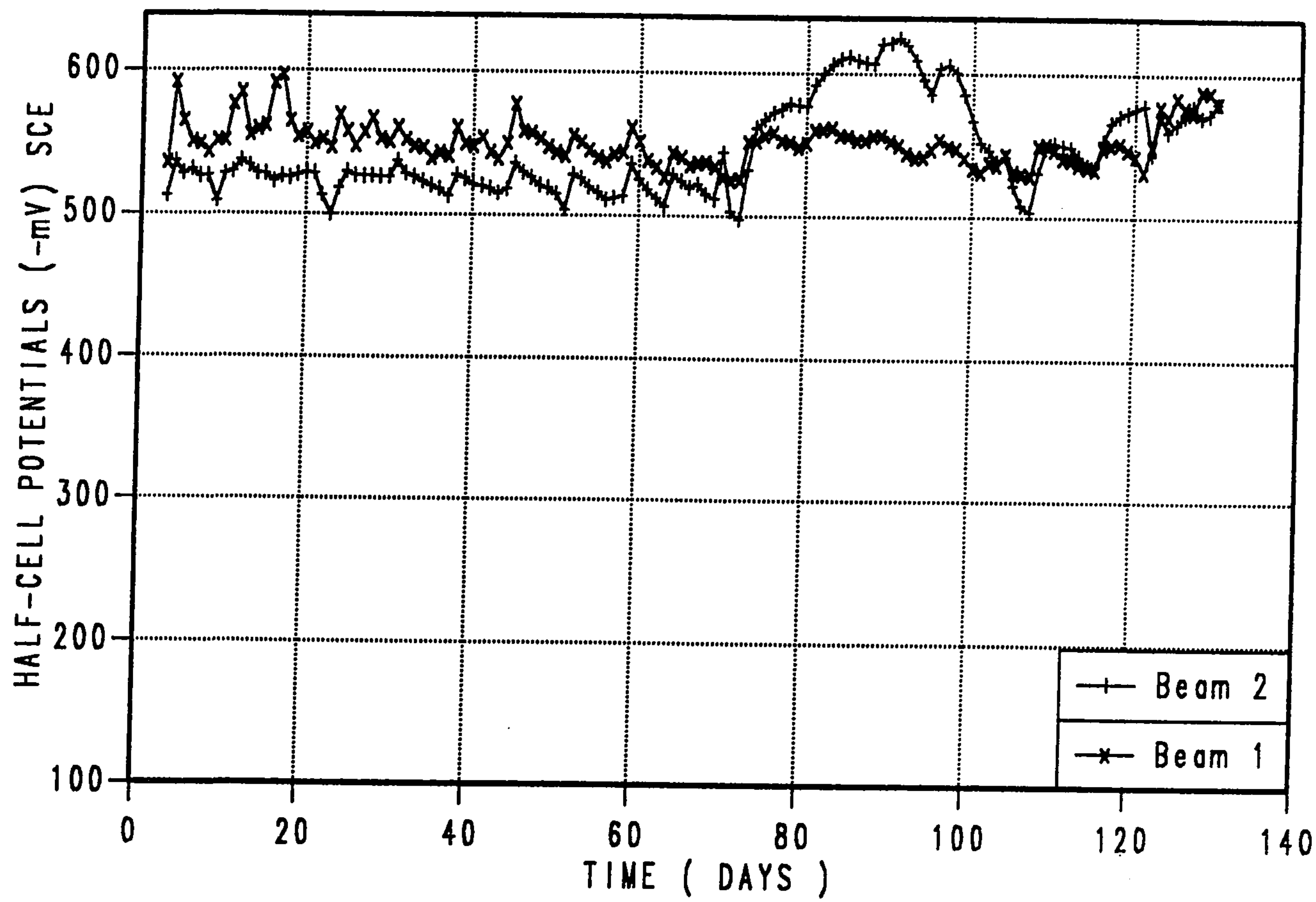


Fig. 4.15 Half-Cell Potential Data for Beams Repaired with Polymer Modified Cementitious Mortar and Subjected to Thermal Cycling

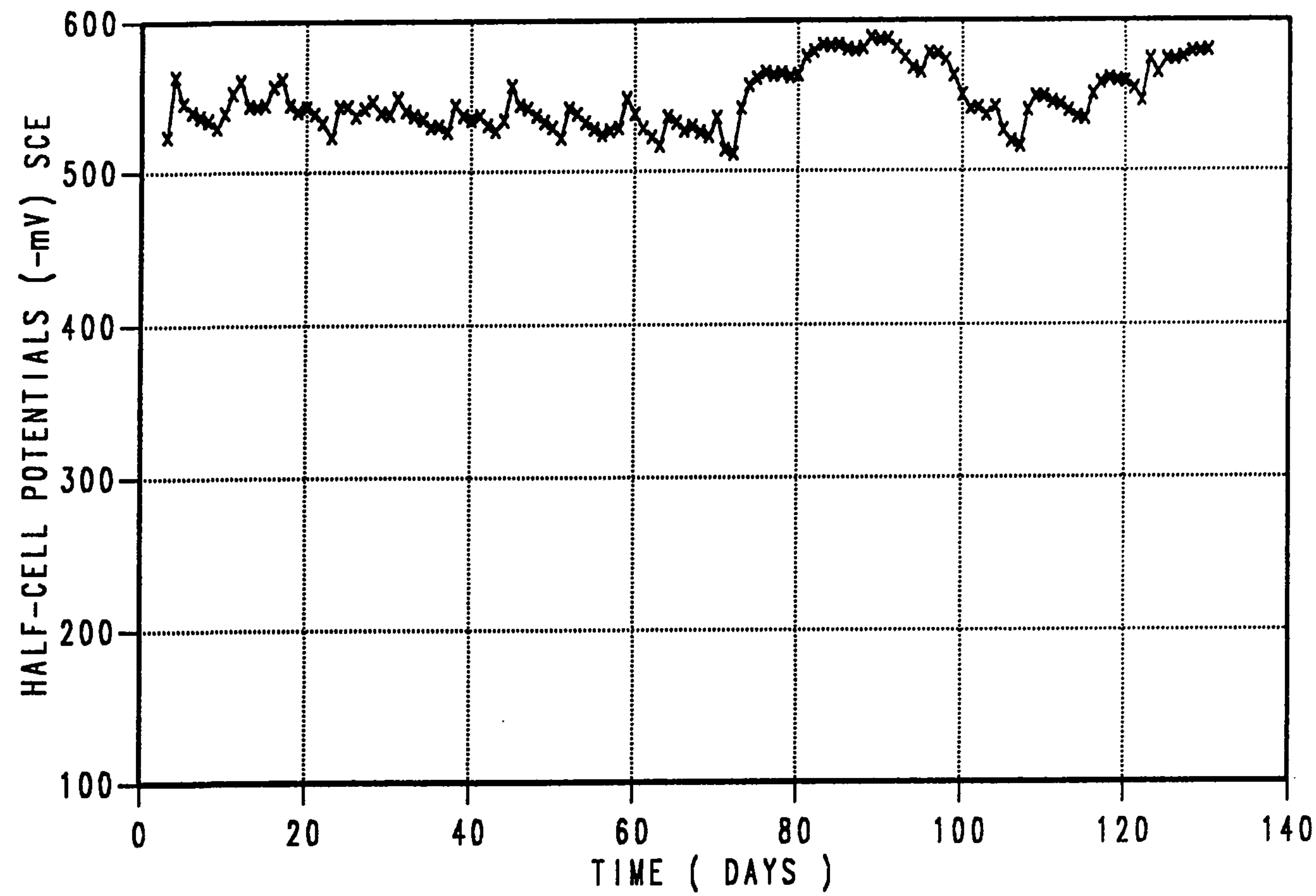


Fig. 4.16 Average Half-Cell Readings for Beams Repaired with polymer Modified Cementitious Mortar and Subjected to Thermal cycling

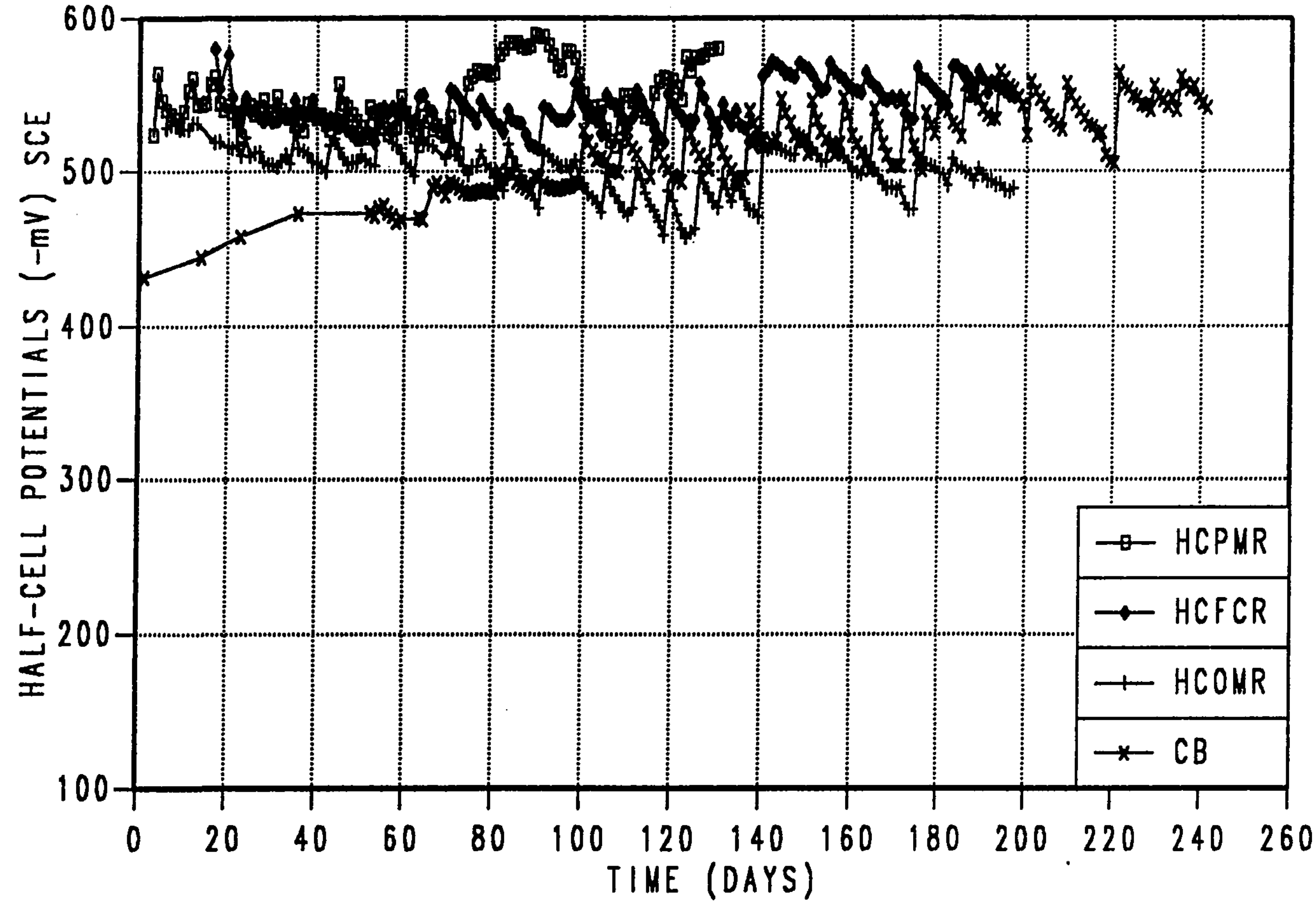


Fig. 4.17: A comparison of Average Half-Cell Potentials for Repaired and Control Beams Subjected to Thermal Cycling

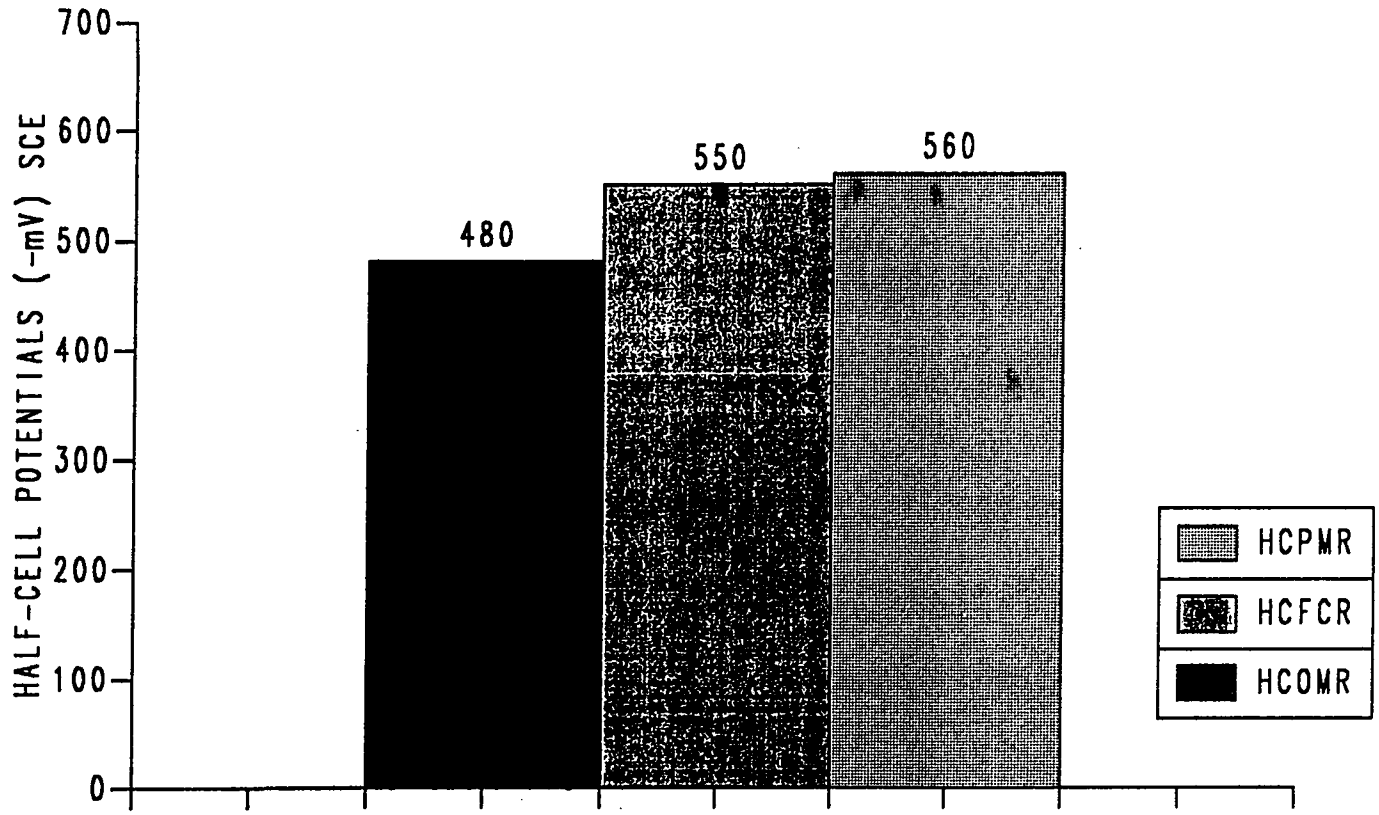


Fig 4.18: Average Potentials in repaired Beams Subjected to Thermal Cycling After 120 Days of Exposure to Chloride Solution

The half-cell potentials of rebars in beams which were subjected to heat-cool cycling are compared with the half-cell potentials values of rebars in normally cured repaired beams in Figures 4.19 through 4.21. The average half-cell potentials in beams repaired with ordinary mortar are plotted against time in Figure 4.19. The higher curve is for specimens which were subjected to heat-cool cycling, while the lower curve is for normal cured specimens. In Figure 4.20 the average half-cell potentials of rebars in beams repaired with ferrocement mortar are shown. Again, the higher curve is for beams subjected to thermal cycling, while the lower curve is for normally cured beams. The average half-cell potentials of beams repaired with polymer modified cementitious mortar are shown in Figure 4.21. These data indicated that the half-cell potentials of rebars in repaired beams subjected to thermal cycling were higher (more negative) than those in normally cured beams. This means that the corrosion resistance of the repaired beams is reduced when they are subjected to thermal cycling. The half-cell potential values are however, lower than normally cured plain concrete specimens.

4.1.2 Potential Noise Measurements

The half-cell potentials for one beam from each group were measured at 15 seconds interval for 15 minutes. Figures 4.22 through 4.28 show the variation of half-cell potentials with time. These potentials which were measured in milli volts indicate the electrochemical noise due to the corrosion activity.

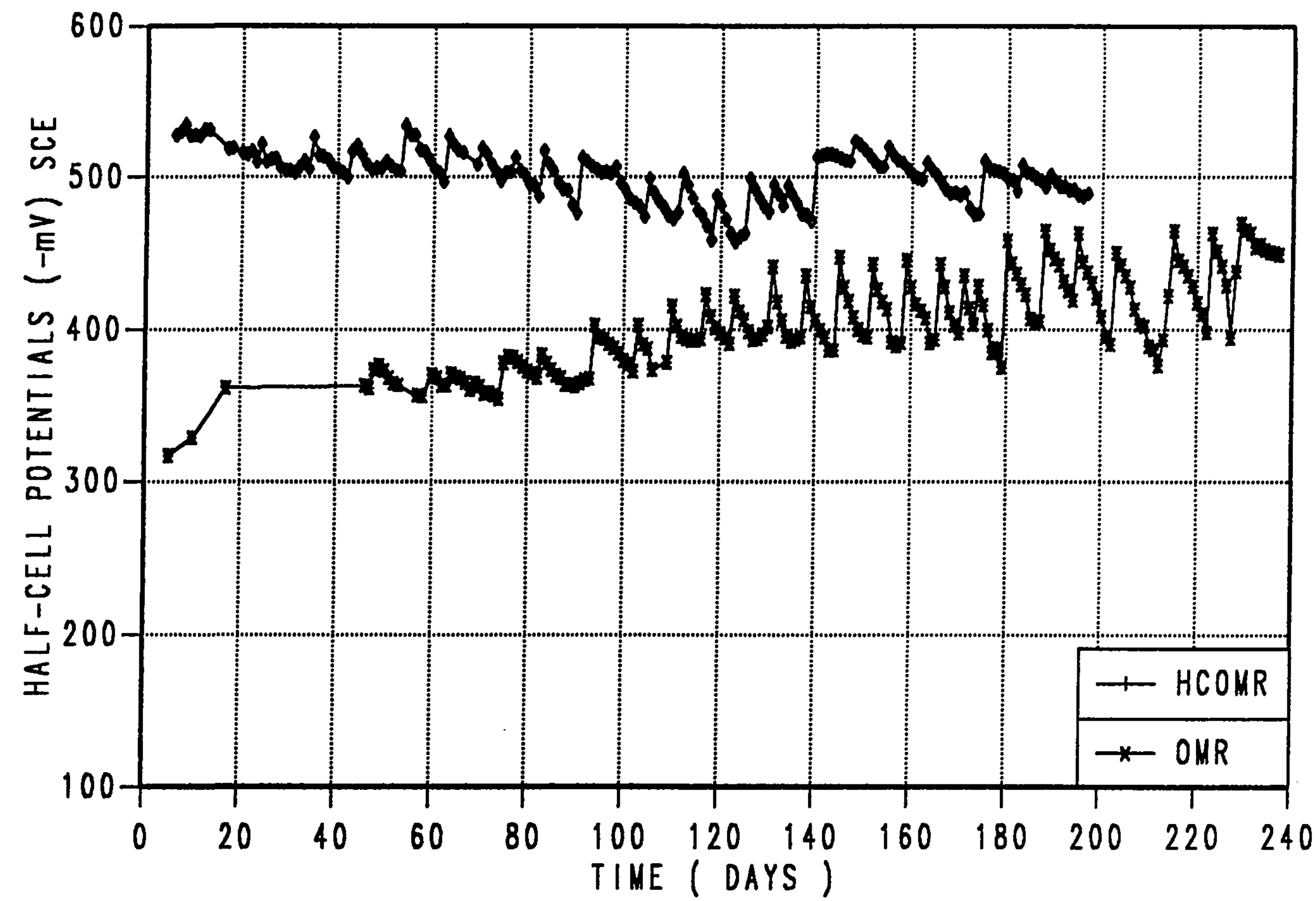


Fig. 4.19: Average Half-Cell Potential Data for Thermal Cycled and Normlly Cured Beams Repaired with Ordinary Cement Mortar

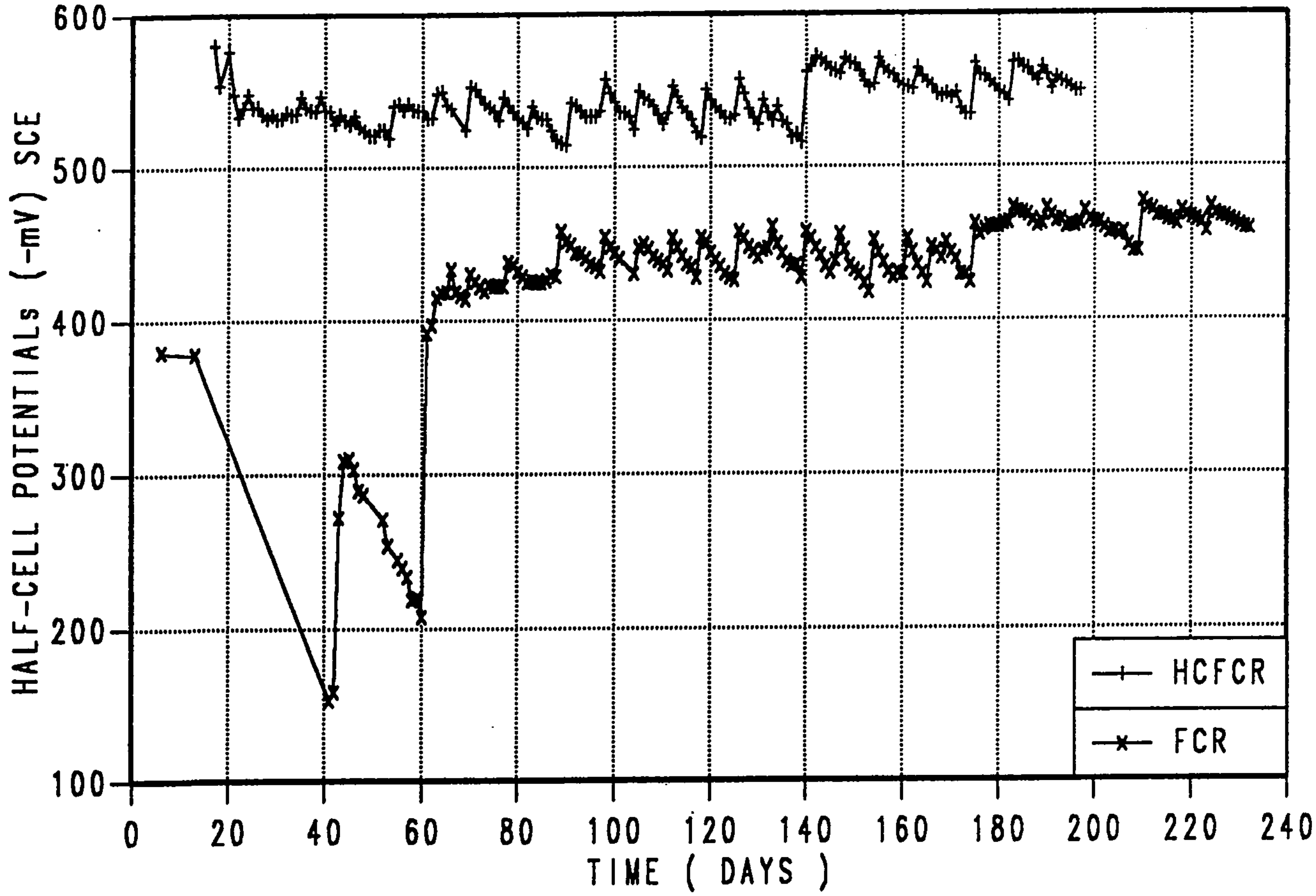


Fig. 4.20: Average Half-Cell Potential Data for Thermal Cycled and Normlly Cured Beams Repaired with Ferrocement Mortar

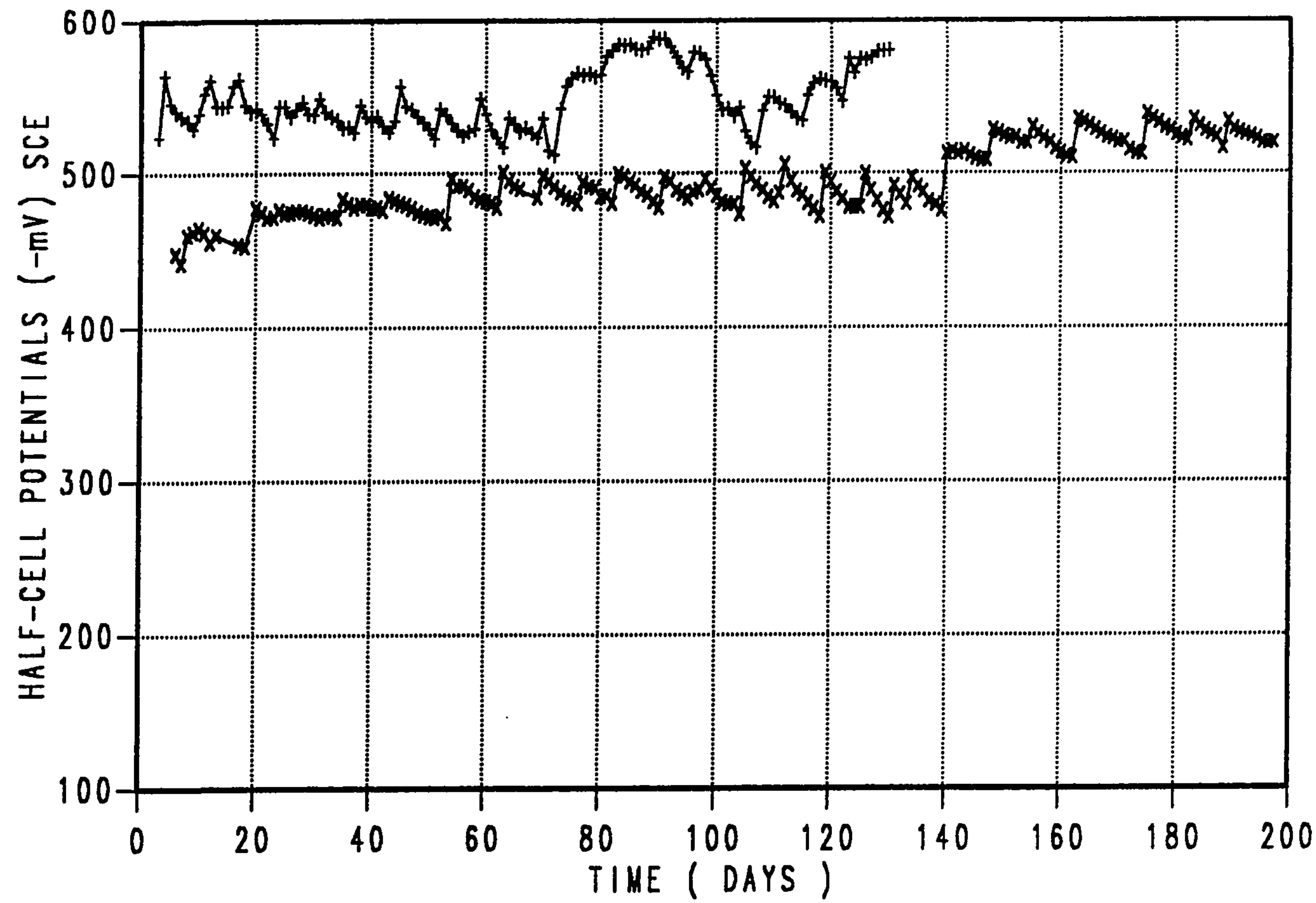


Fig. 4.21: Average Half-Cell Potential Data for Thermal Cycled and Normlly Cured Beams Repaired with Polymer Modified Cementitious Mortar

Figure 4.22 shows variation of the half-cell potential noise plotted against time for control beam, while Figures 4.23 through 4.25 show the half-cell potential noise plotted against time for beams repaired with ordinary cement mortar, ferrocement mortar and polymer modified cementitious mortar respectively. Figures 4.26 through 4.28 show the variation of half-cell potential noise in repaired beams subjected to thermal cycling. Table 4.1 shows the standard deviation of the half-cell potential noise data for the control and repaired beams.

4.1.3 Corrosion Rate in Beam Samples

The rate of corrosion of rebars in the beam samples was determined using Tafel Plot technique. Two samples from each group were tested. The Tafel plots for one sample from each group are shown in Figures 4.29 to 4.34. The corrosion rate of rebars in each beam was calculated using these Tafel plots. The average corrosion rate values are shown in Table 4.2 and plotted in Figure 4.35. The corrosion rate of rebars in normal beams was 0.5 mils per year (mpy). The corrosion rate of rebars in repaired beams were in the range of 0.29 to 0.42 mpy. The corrosion rate data exhibited a trend similar to that indicated by the half-cell potential data. The corrosion rate of rebars in beams repaired with ordinary cement mortar was lower than the corrosion rate of rebars in beams repaired with ferrocement mortar and polymer cement mortar. The corrosion rate of rebars repaired with polymer modified cement mortar was slightly higher than the corrosion rate of rebars in beams repaired with ferrocement mortar. The corrosion rate of rebars in repaired beams subjected to

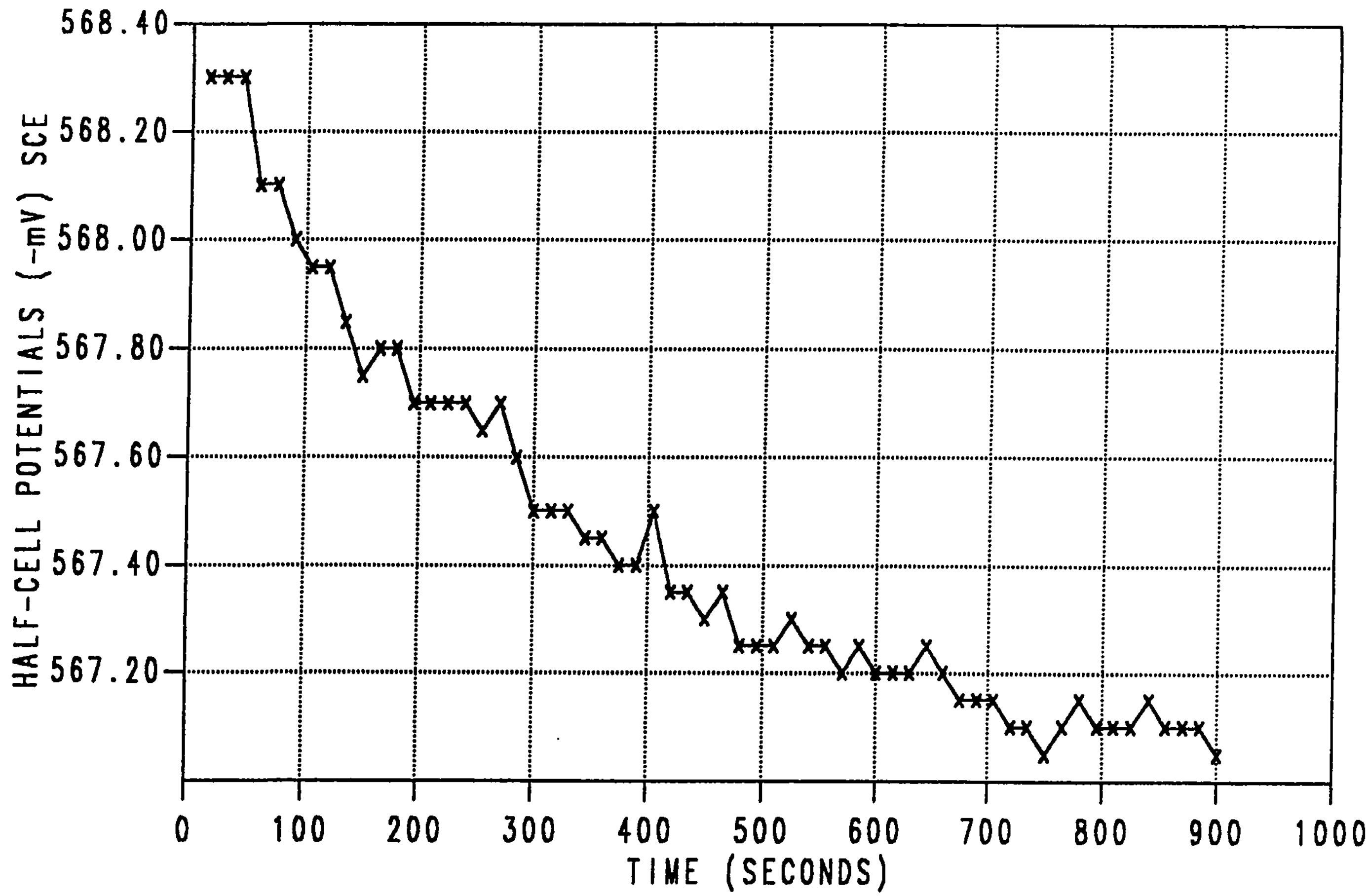


Fig. 4.22 Potential Noise Data For Control Beam

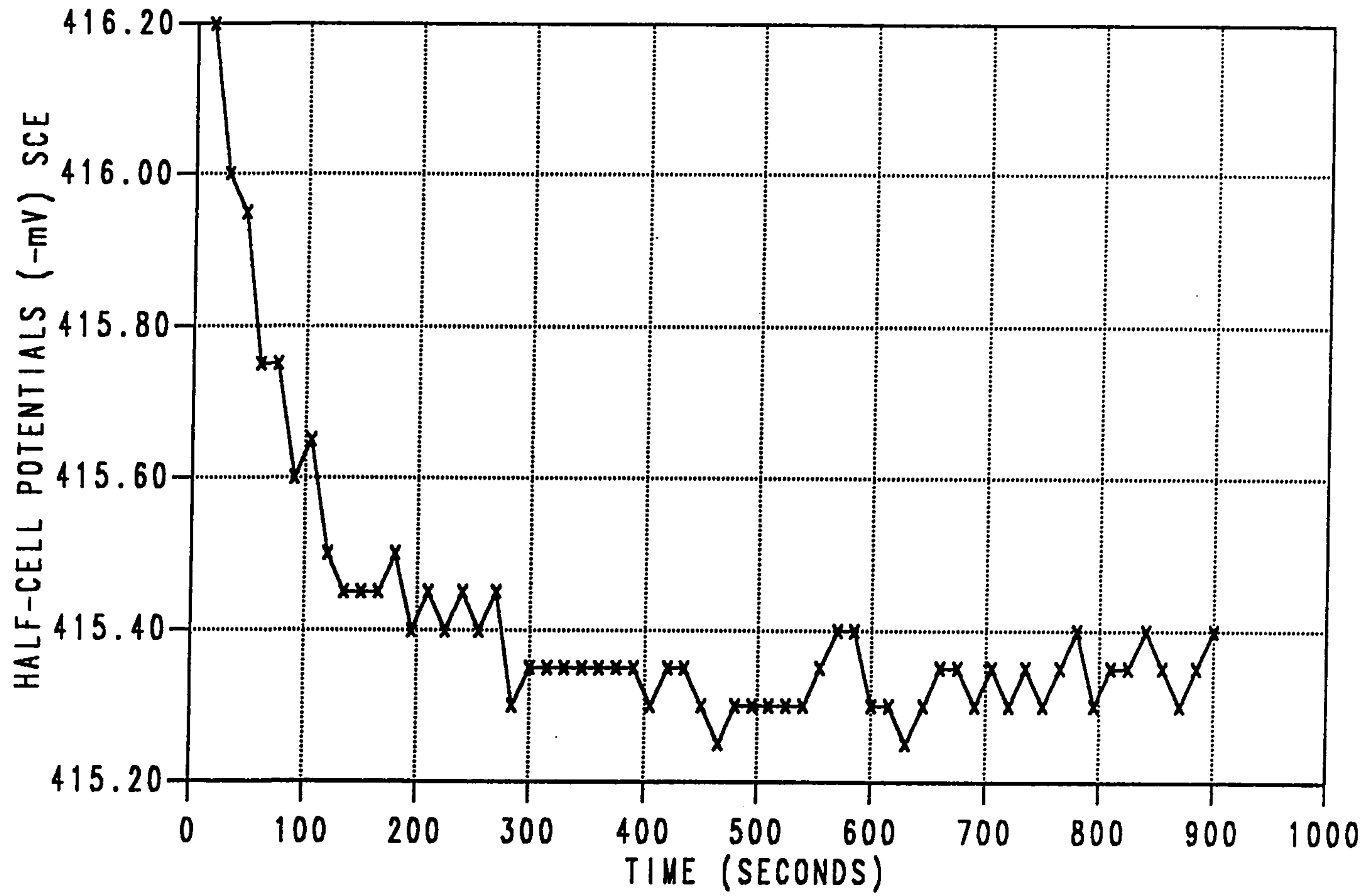


Fig. 4.23: Potential Noise Data for Beams Repaired with Ordinary Cement Mortar

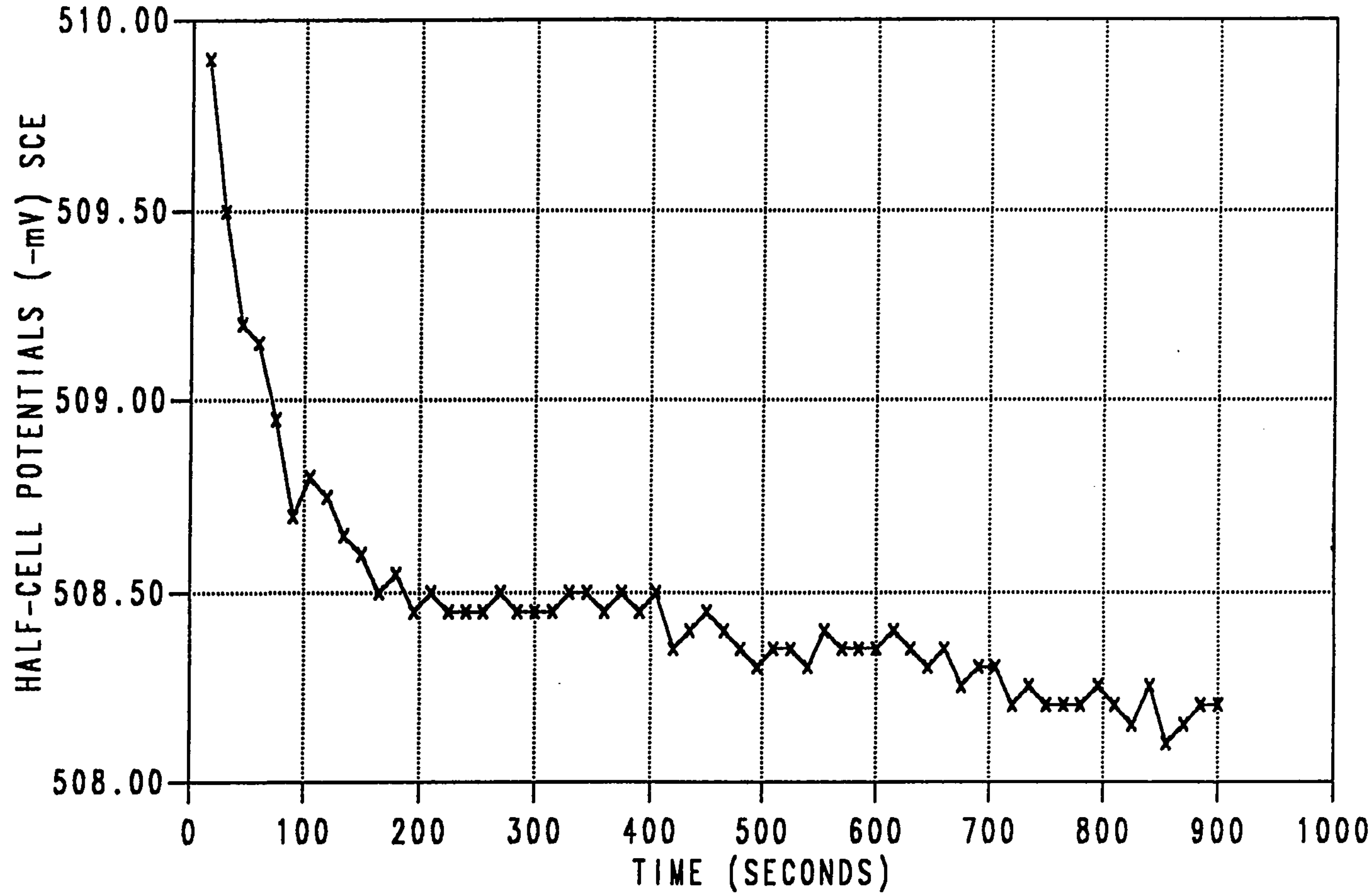


Fig. 4.24: Potential Noise Data for Beams Repaired with Ferrocement Mortar

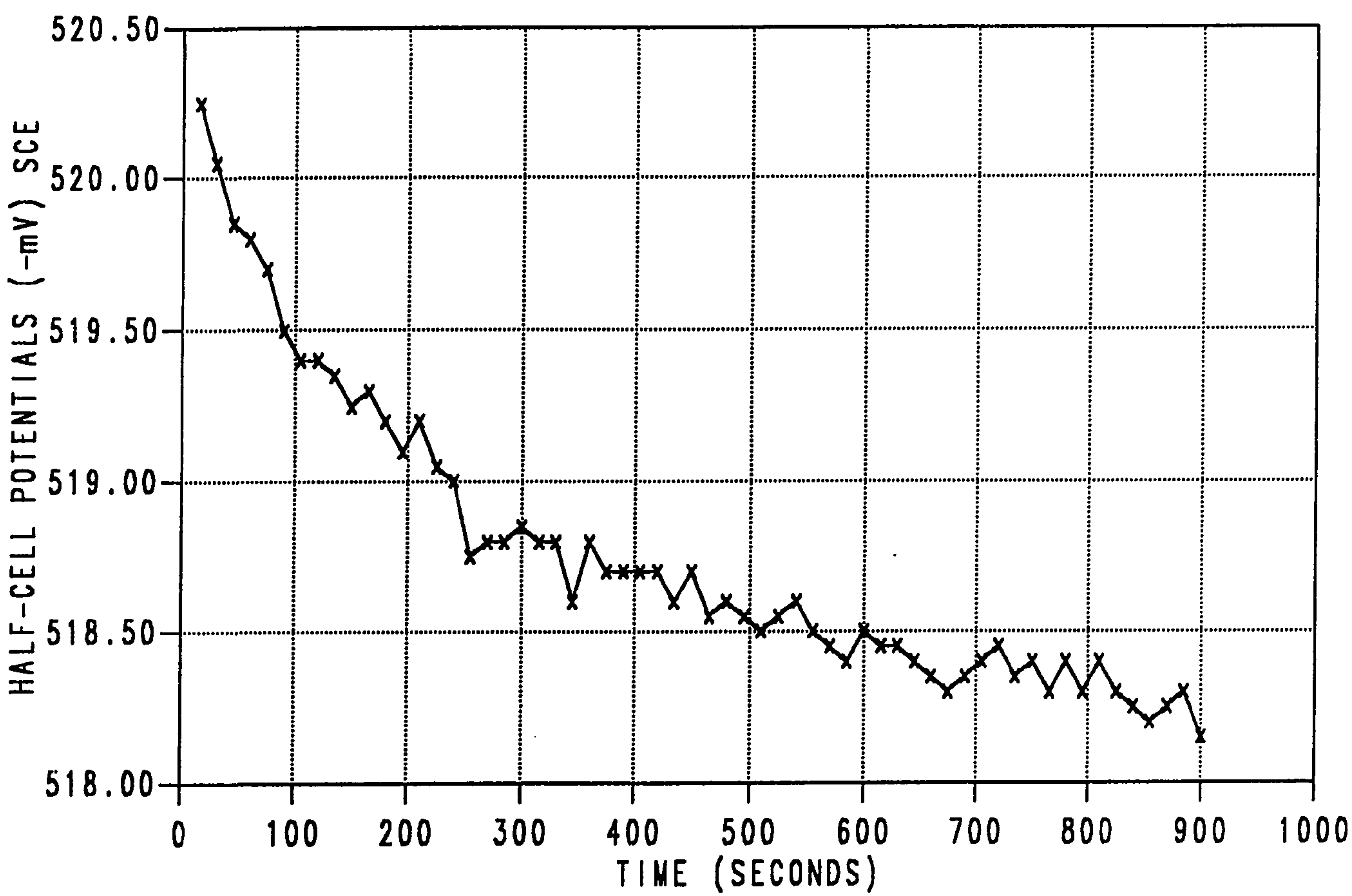


Fig. 4.25 Potential Noise Data for Beams Repaired with Polymer Modified Cementitious Mortar

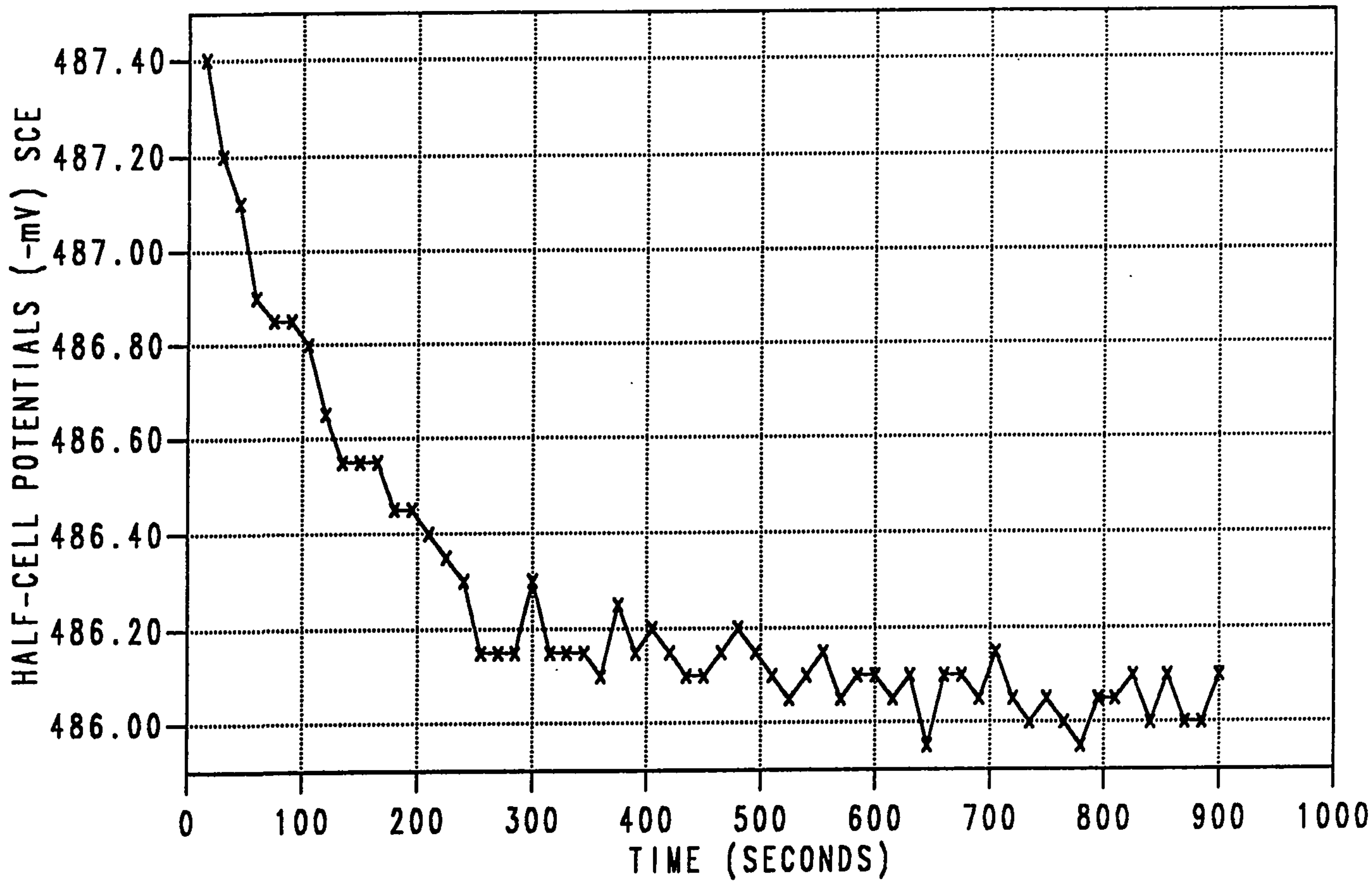


Fig. 4.26: Potential Noise Data for Beams Repaired with Ordinary Cementitious Mortar and Subjected to Thermal Cycling

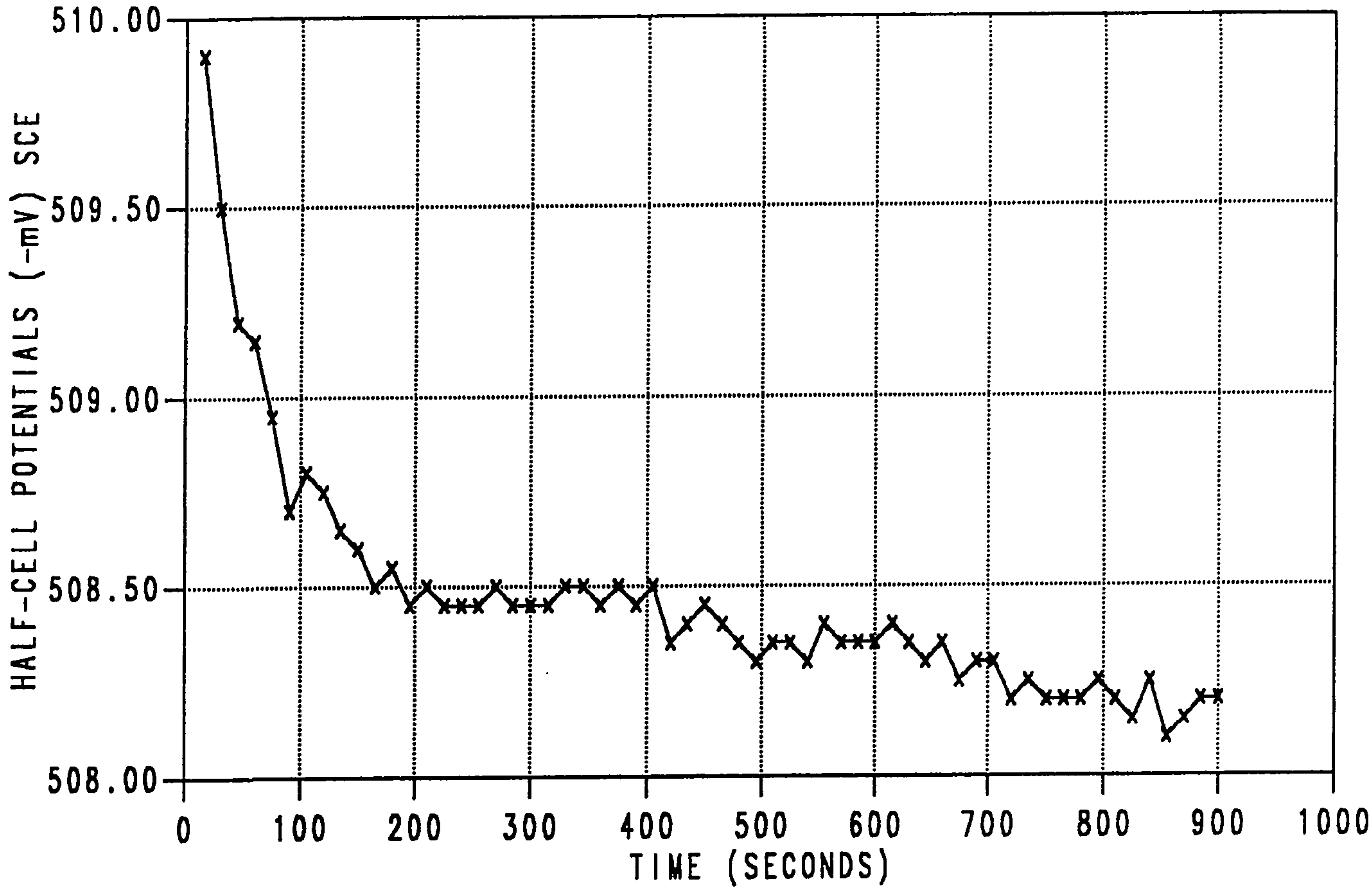


Fig. 4.27: Potential Noise Data for Beams Repaired with Ferrocement Mortar and Subjected to Thermal Cycling

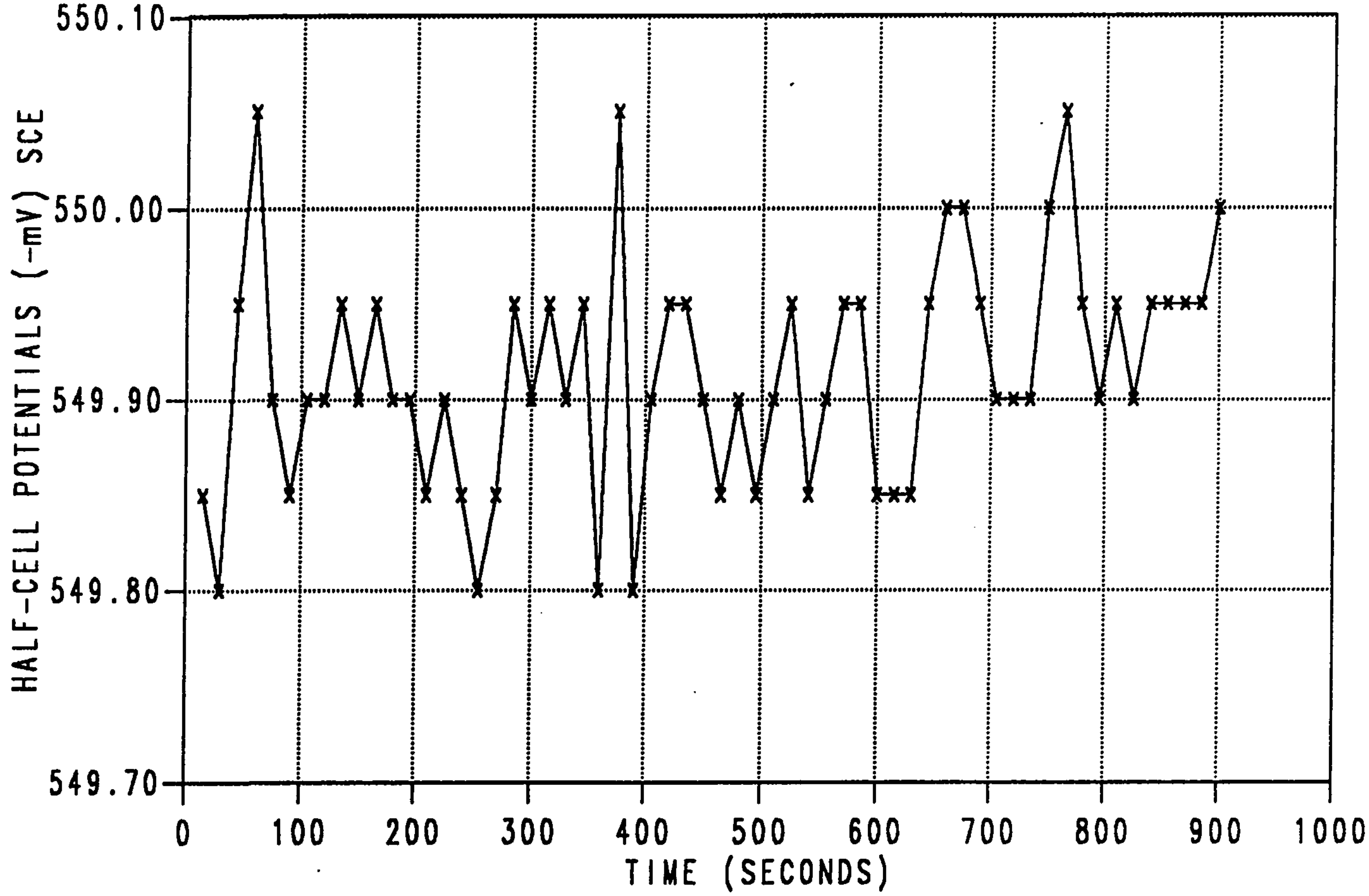


Fig. 4.28: Potential Noise Data for Beams Repaired with Polymer Modified Cementitious Mortar and Subjected to Thermal Cycling

Table 4.1 Standard Deviation of Half-Cell Potential Noise Data

Specimen Type	Standard Deviation (-mV)
Control Beams	0.350
Beams Repaired with Ordinary mortar	0.169
Beams Repaired with Ferrocement	0.318
Beams Repaired with Polymer Mortar	0.493
Beams Repaired with Ordinary Mortar and Subjected to Thermal Cycling	0.323
Beams Repaired with Ferrocement and Subjected to Thermal Cycling	0.129
Beams Repaired with Polymer Mortar and Subjected to Thermal Cycling	0.060

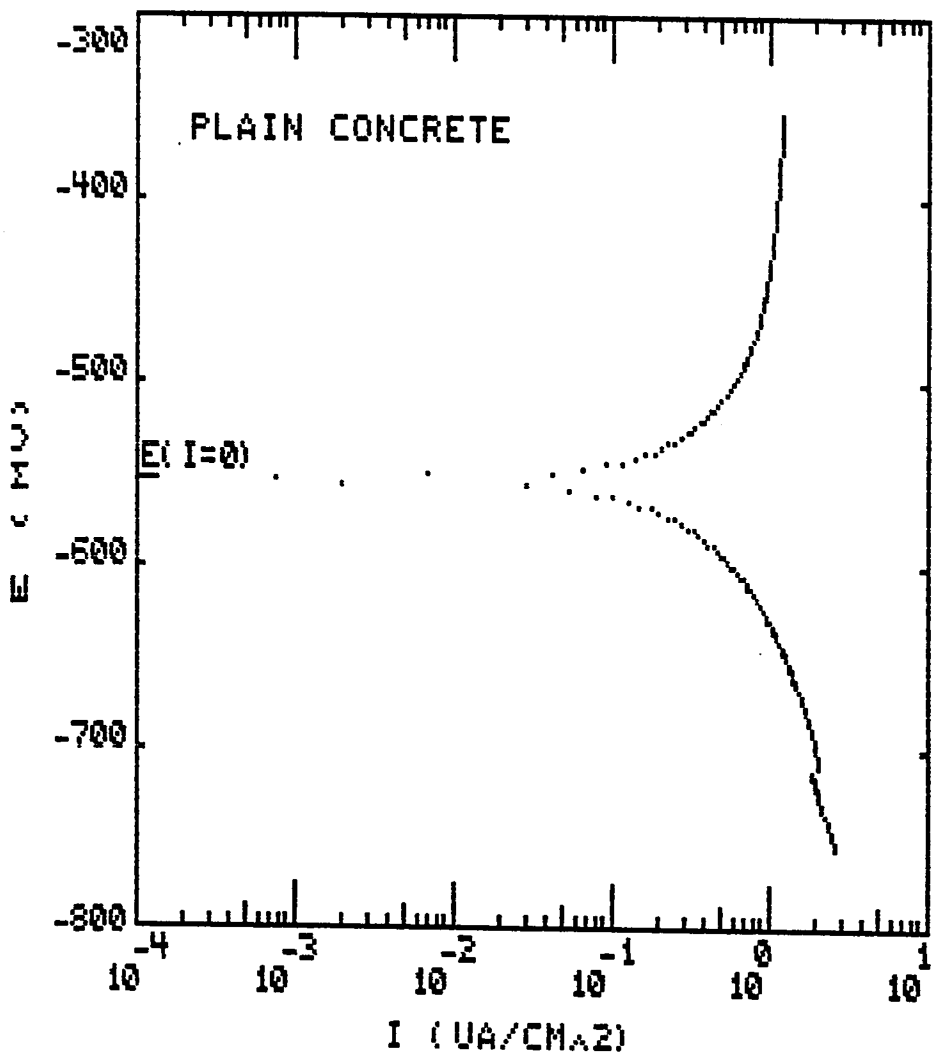


Figure 4.29: Tafel Plot for Plain Concrete Beams

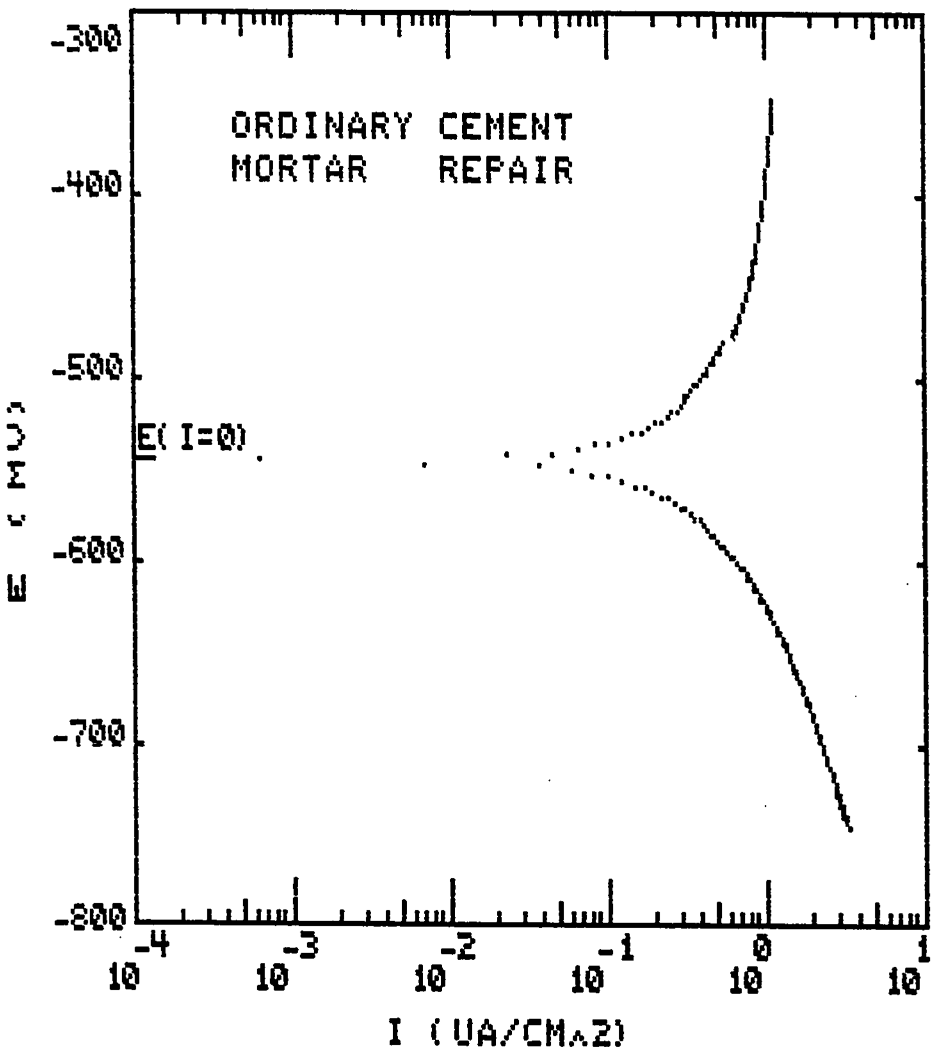


Figure 4.30: Tafel Plot for Beams Repaired with Ordinary Mortar

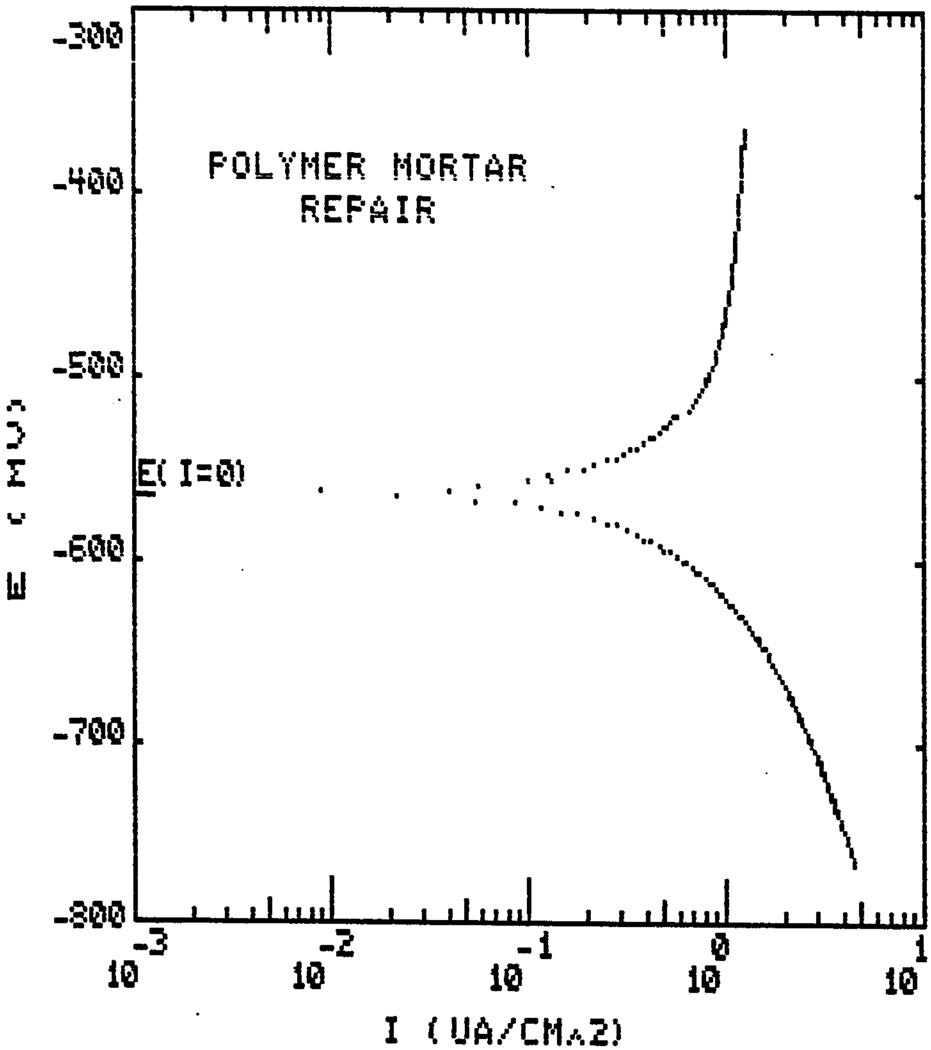


Figure 4.31: Tafel Plot for Beams Repaired with Polymer Modified Cementitious Mortar

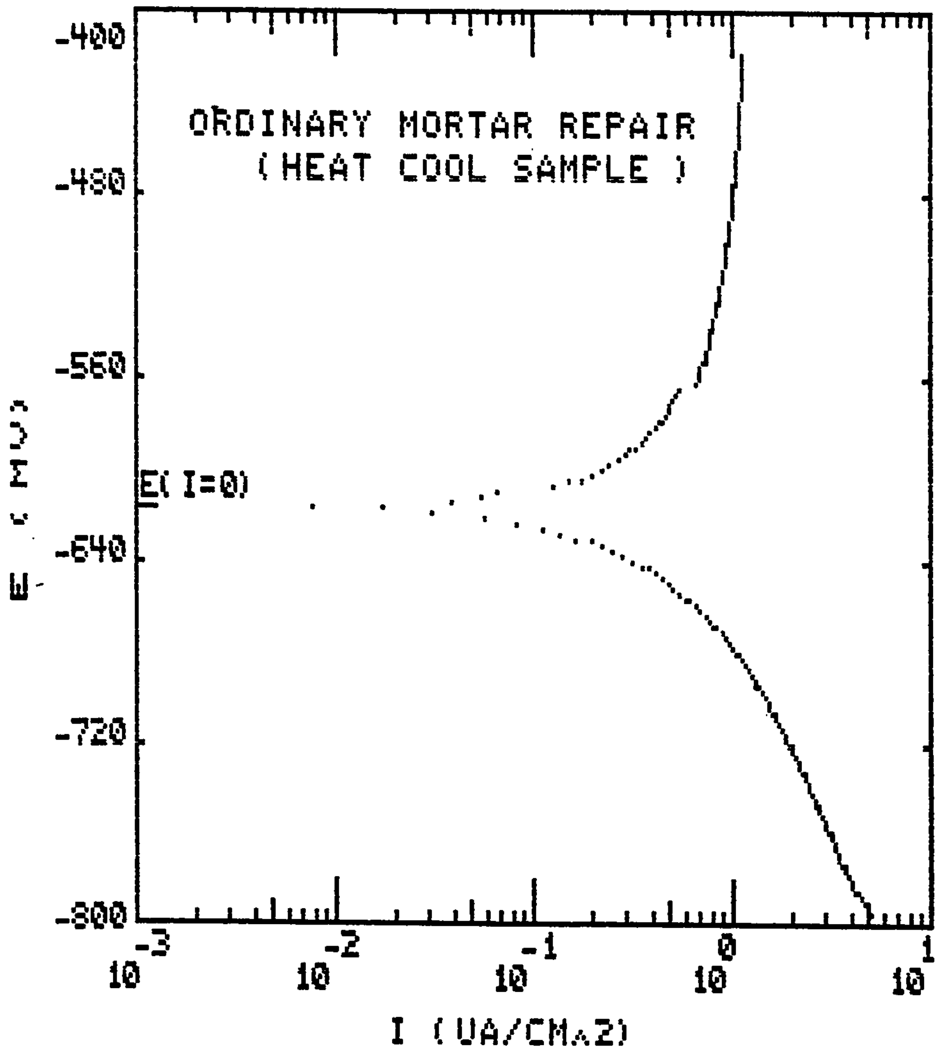


Figure 4.32: Tafel Plot for Beams Repaired with Ordinary Cement Mortar and Subjected to Thermal Cycling

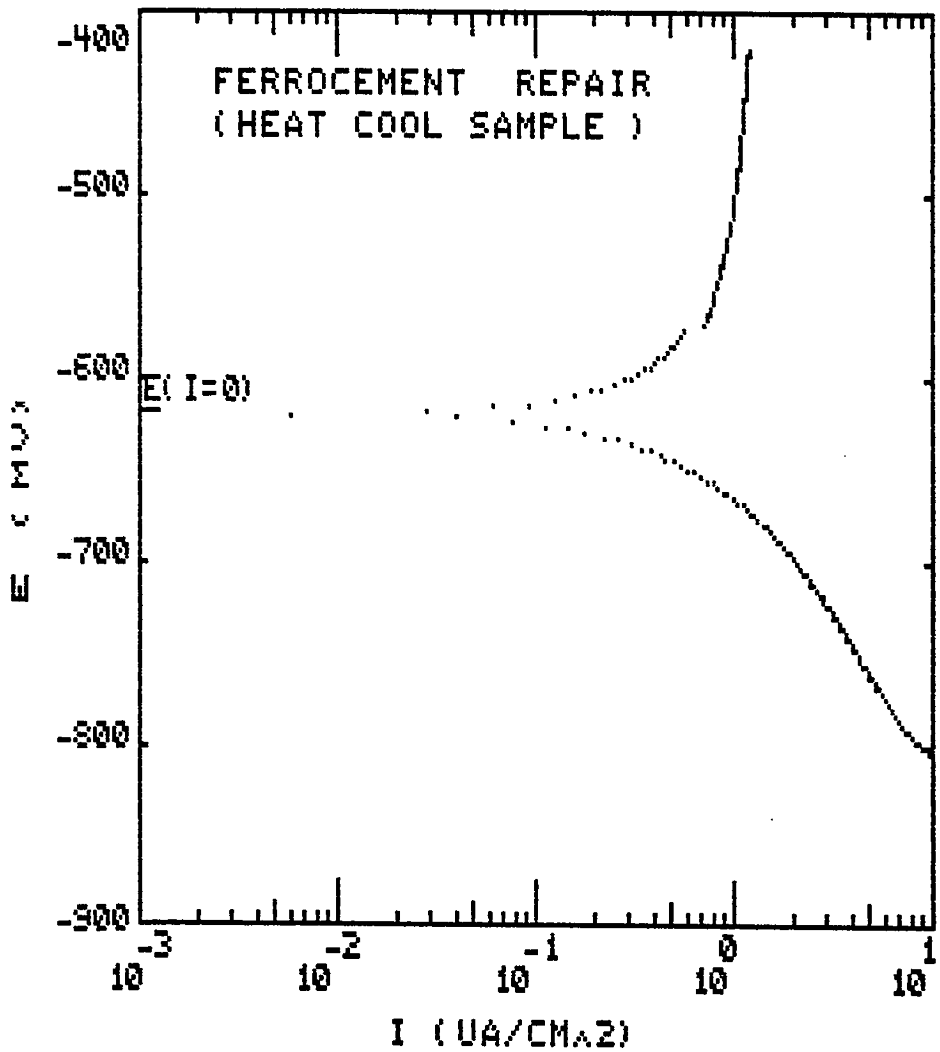


Figure 4.33: Tafel Plot for Beams Repaired with Ferrocement and Subjected to Thermal Cycling

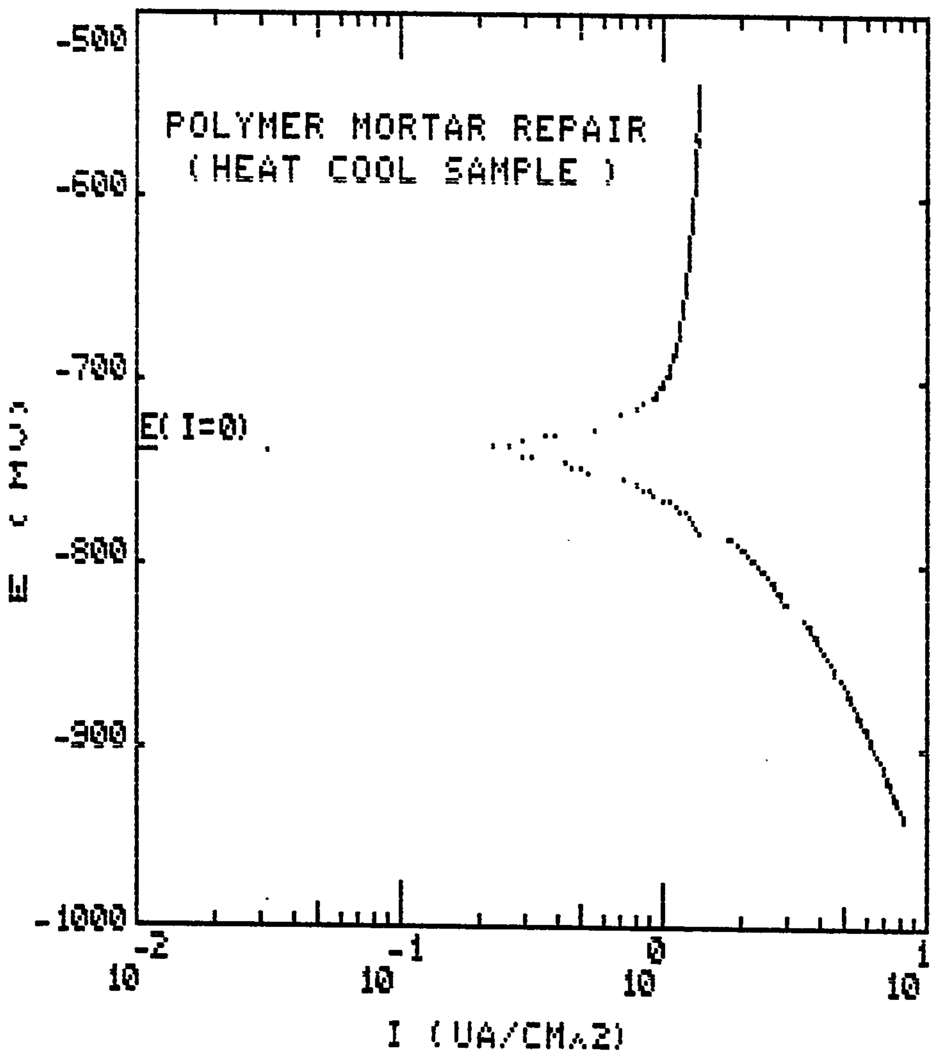


Figure 4.34: Tafel Plot for Beams Repaired with Polymer Mortar and Subjected to Thermal Cycling

Table 4.2 : Corrosion Rate of bars in Repaired and Control Beams

Sample Type	Corrosion Rate (mpy)
Control Beams	0.50
Beams Repaired with Ordinary mortar	0.29
Beams Repaired with Ferrocement Mortar	0.37
Beams Repaired with Polymer Cement Mortar	0.42
Beams Repaired with Ordinary mortar and Subjected to Thermal Cycling	0.50
Beams Repaired with Ferrocement and Subjected to Thermal Cycling	0.49
Beams Repaired with Polymer Mortar and Subjected to Tharmal Cycling	0.52

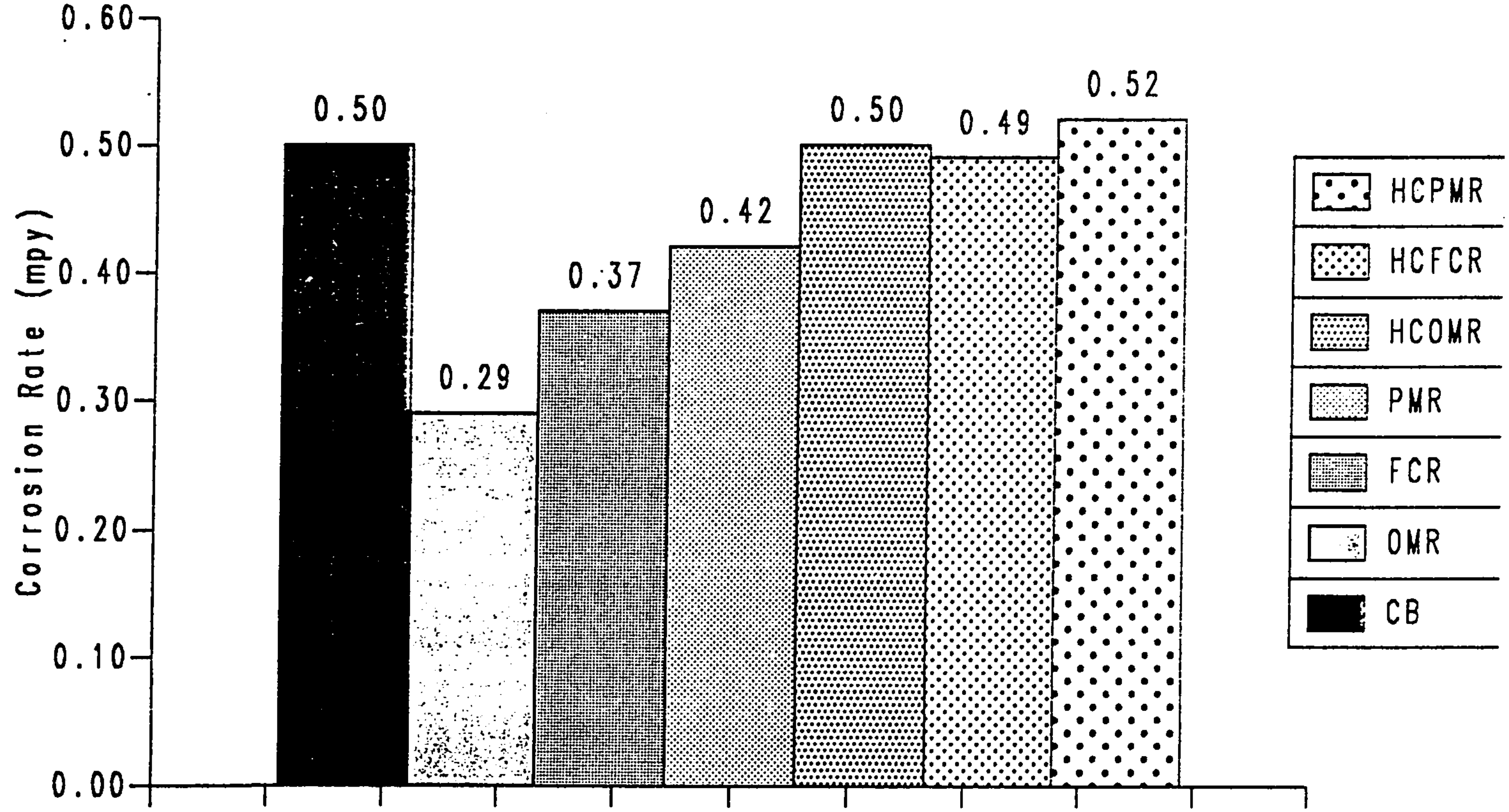


Fig. 4.35: Average Corrosion Rates of Rebars in all Beams

thermal cycling were in the range of 0.5 to 0.52 mpy. This indicates that thermal cycling decreased the corrosion resistance of repaired beams.

4.2 Results of Permeability Tests

The repair materials were tested to determine the water and chloride permeability. In addition to plain concrete and the repair materials, silica fume mortar, in which 10% silica fume was used as a replacement of cement, was also tested for its permeability to water and chloride ions. The results of water and chloride permeability are shown in Tables 4.3 and 4.4 and plotted in Figures 4.36 through 4.40.

4.2.1 Water Permeability Test

The water permeability tests, were conducted according to German Standards, DIN 1048, on ordinary cementitious mortar, ferrocement mortar, polymer modified cementitious mortar, silica-fume mortar and plain concrete specimens. The results of these tests are shown in Table 4.3 and Figure 4.36.

The depth of penetration in plain concrete samples which were not subjected to heat-cool cycling was 30 mm. The depth of water penetration in the other samples was in the range of 14 to 26 mm. The depth of water penetration increased with the number of heat cycles. The relationship between the depth of water penetration and number of heat-cool cycles was approximately linear. The depth of water penetration after 120 heat-cool cycles was 85 mm in plain concrete specimens, whereas it was in the range of 45-75 mm in samples made with the repair materials.

Table 4.3: Results of Water Permeability Test

Sample Type	Permeability After Thermal Cycling (mm)				
	0	10	30	60	120
Plain Concrete	30.0	45.0	55.0	63.0	85.0
Ordinary Cement Mortar	20.5	33.0	45.0	56.3	75.0
Ferrocement Mortar	26.0	29.0	43.0	48.3	68.3
Polymer Cement Mortar	14.3	18.7	26.0	37.0	45.3
Silica Fume Mortar	19.5	24.5	30.7	45.0	61.0

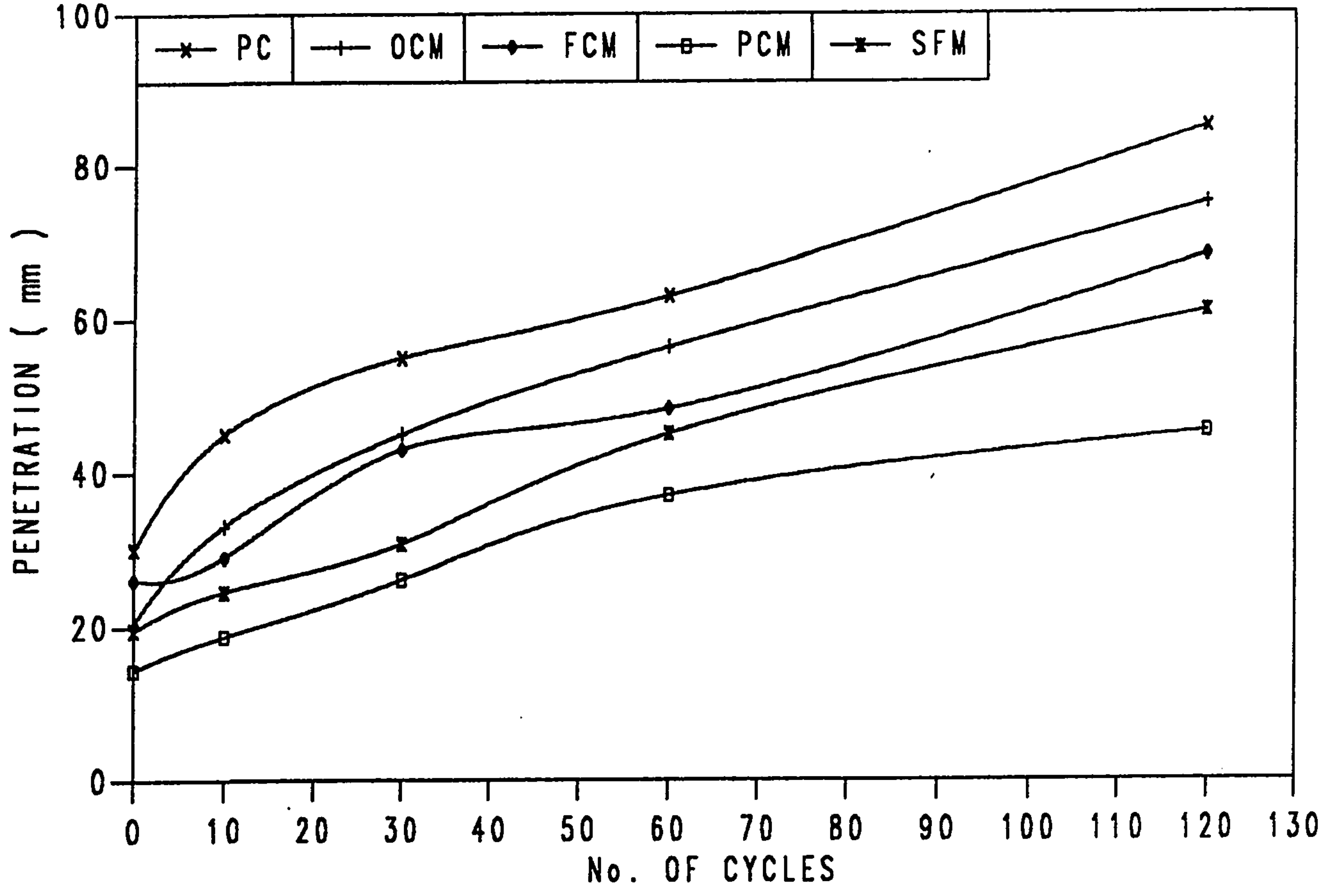


Fig. 4.36: Water Permeability Results.

This indicates that the performance of the repair materials in the water permeability test is better than the performance of plain concrete. Polymer modified cementitious mortar specimens exhibited the least water permeability followed by silica fume, ferrocement mortar and ordinary cement mortar specimens respectively. These results are consistent with properties of each material. The water permeability of plain concrete is higher than that of ordinary mortar. This is because of the heterogeneous nature of concrete and due to the microcracking present at the interface of the aggregate and the concrete paste. The transition zone is weak and vulnerable to cracking due to differential strains between the cement paste and aggregate induced generally by drying shrinkage and thermal shrinkage. Polymer modified cementitious mortar and silica fume mortar specimens exhibited lower water permeability. This is due to the reduction of size of voids in hydrated cement paste due to the addition of special additives to these materials. In ferrocement mortar the presence of wire mesh may arrest the microcracks due to thermal and drying shrinkage.

4.2.2 Chloride Permeability

The chloride permeability test was performed to determine the diffusion of chloride ions in plain concrete specimens and specimens prepared using the repair materials. This test was carried out according to AASHTO Standard T-277. In this test the current passing through a sample for a 6-hour period is recorded. The total charge passed through a sample which is the area under the time-current curves is used as a performance criteria. The time-current curves for the samples tested in this investigation are shown in Figure 4.37 through 4.40. The total charge passed in each of the specimens, which was calculated using these figures is shown in Table 4.4. The relationship between chloride permeability and the total charge passed is shown in Table 4.5 [55]. Based on this classification the chloride permeability of the materials investigated can be rated as follows.

Sample Type	*Chloride Permeability*
Silical Fume Mortar	Very Low
Polymer Mortar	Low
Plain Concrete	Low
Ordinary Mortar	Moderate

4.3 Impressed Current Test Results

The variation of corrosion current with time when a constant impressed voltage of 4 volts is applied to specimens made of plain concrete, ordinary cementitious mortar, ferrocement mortar, polymer modified cementitious mortar, and silica-fume mortar, are shown in Figures 4.41 through 4.45. The data obtained were analyzed to determine the time for initiation of rebar corrosion. Corrosion is assumed to have initiated at a point where there is a change in the slope of current-time curve. In some samples a sudden change in the current-time curve was noticed. This is probably due to cracking of the material generated by the splitting force exerted by the corrosion product. The introduction of cracks in the

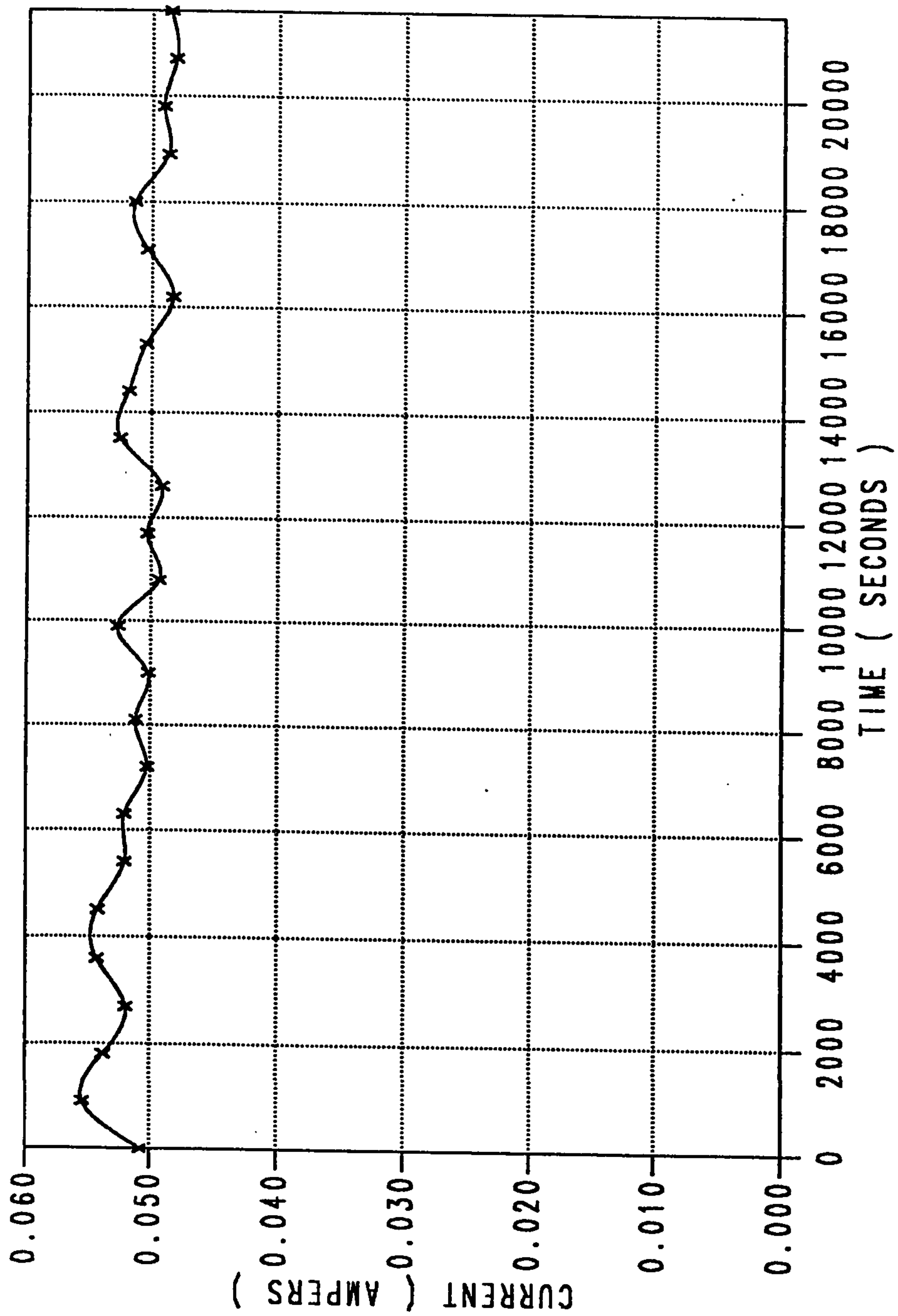


Fig. 4.37: Time-Current Curve for Plain Concrete Samples

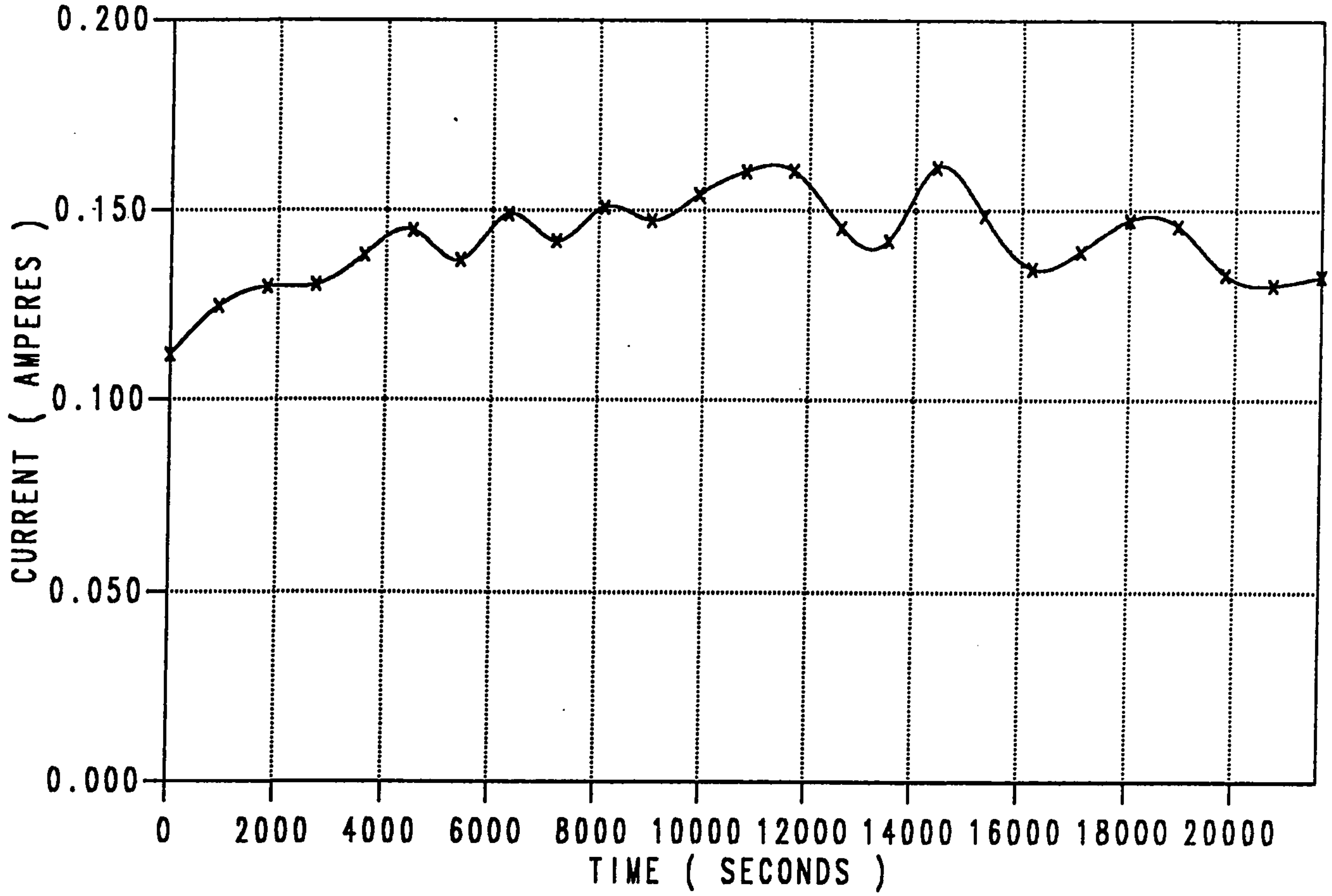


Fig. 4.38 Time-Current Curve for Ordinary Cementitious Mortar Samples

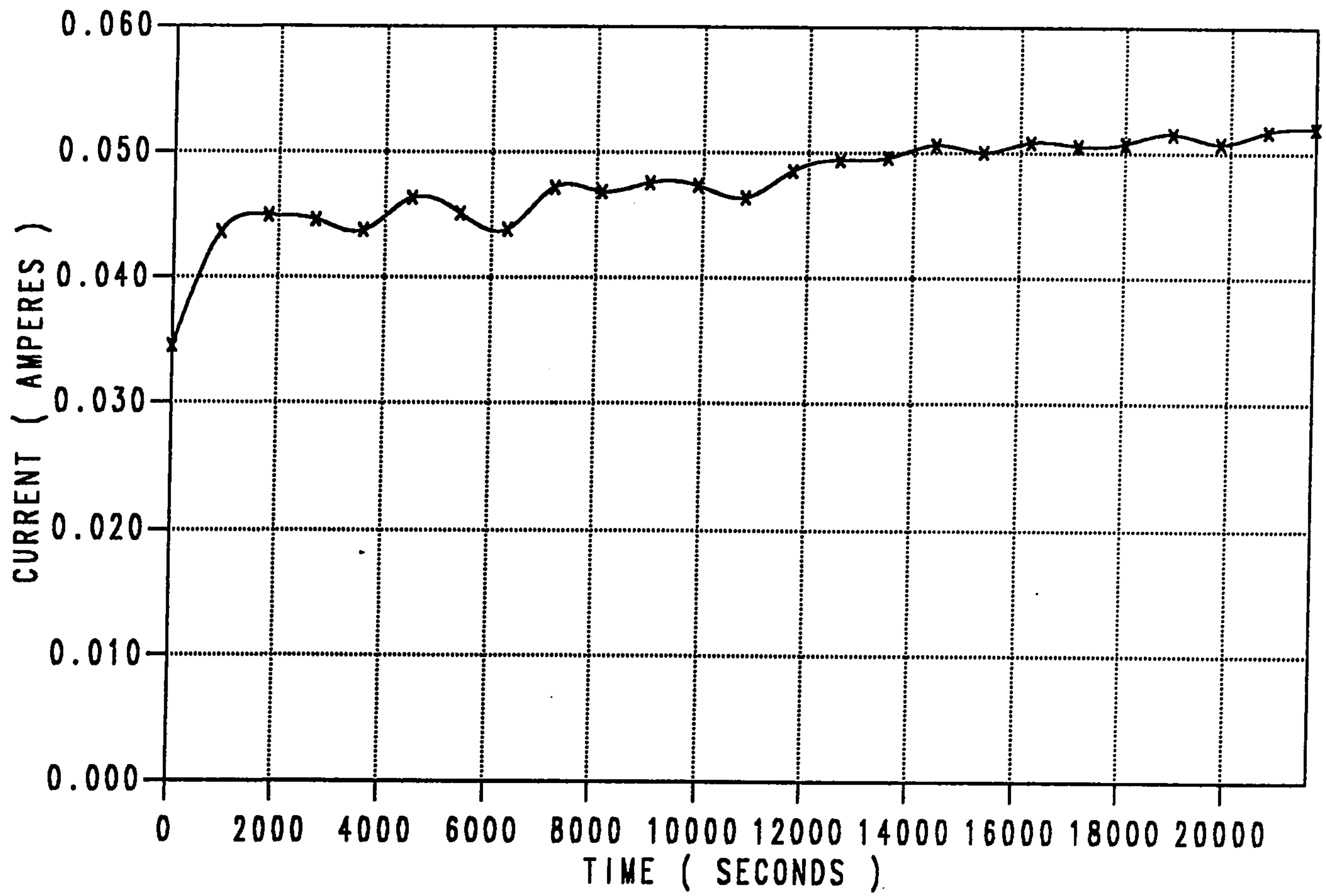


Fig. 4.39 Time-Current Curve for Polymer Cementitious Mortar Samples

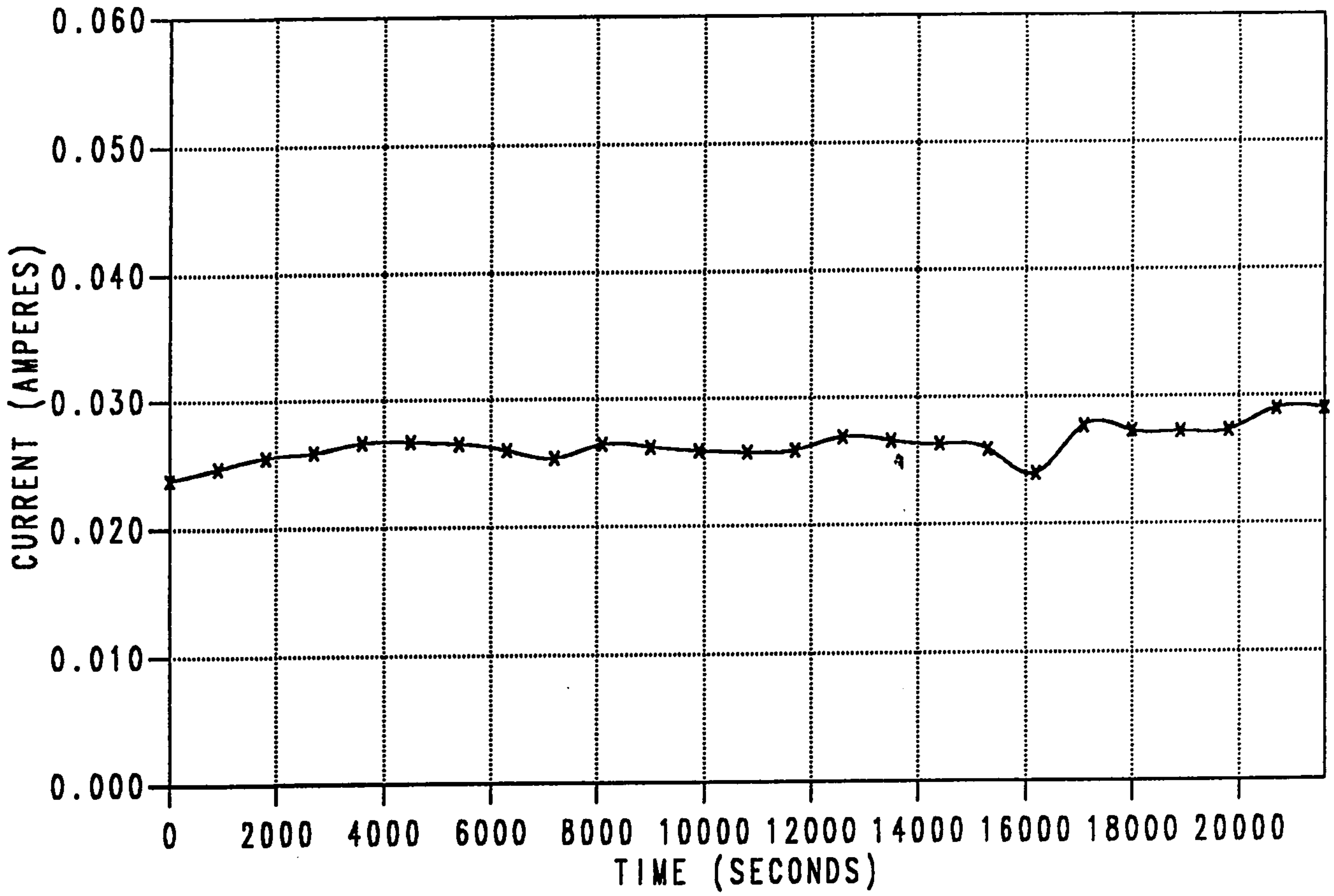


Fig 4.40: Time-Current Curve for Silica fume Mortar Samples

Table 4.4 Results of Chloride Permeability Test

Sample type	Total Charge Passed (Coulomb)
Plain Concrete	1100
Ordinary Cement Mortar	3015
Polymer Modified Mortar	1050
Silica fume Mortar	566

Table 4.5: Relationship Between Charge Passed and Chloride Permeability [55].

Charge Passed (Coulomb)	Chloride Permeability
Greater than 4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very Low
Less than 100	Negligible

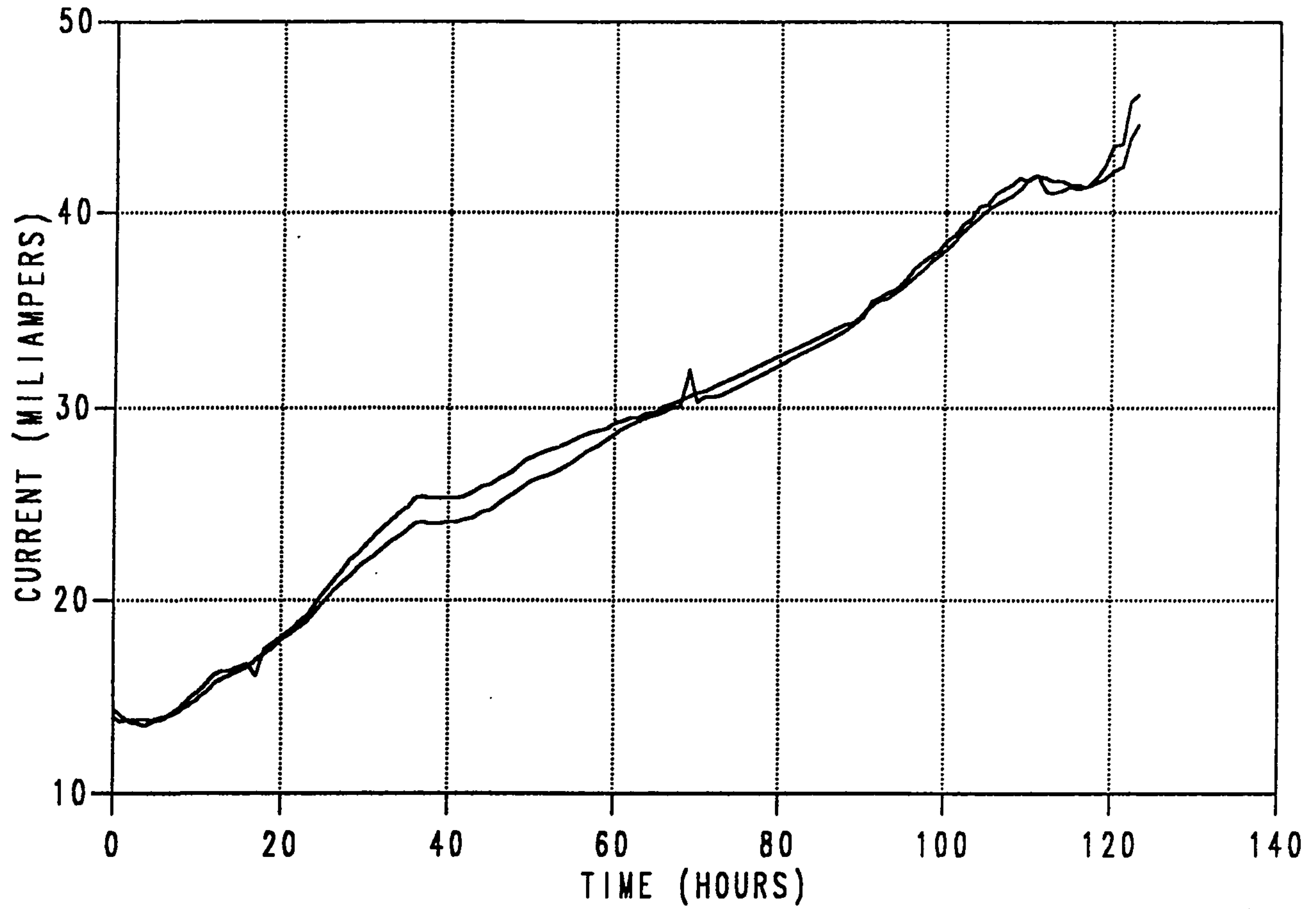


Fig. 4.41 Impressed Current-Time Curves For Plain Concrete Samples

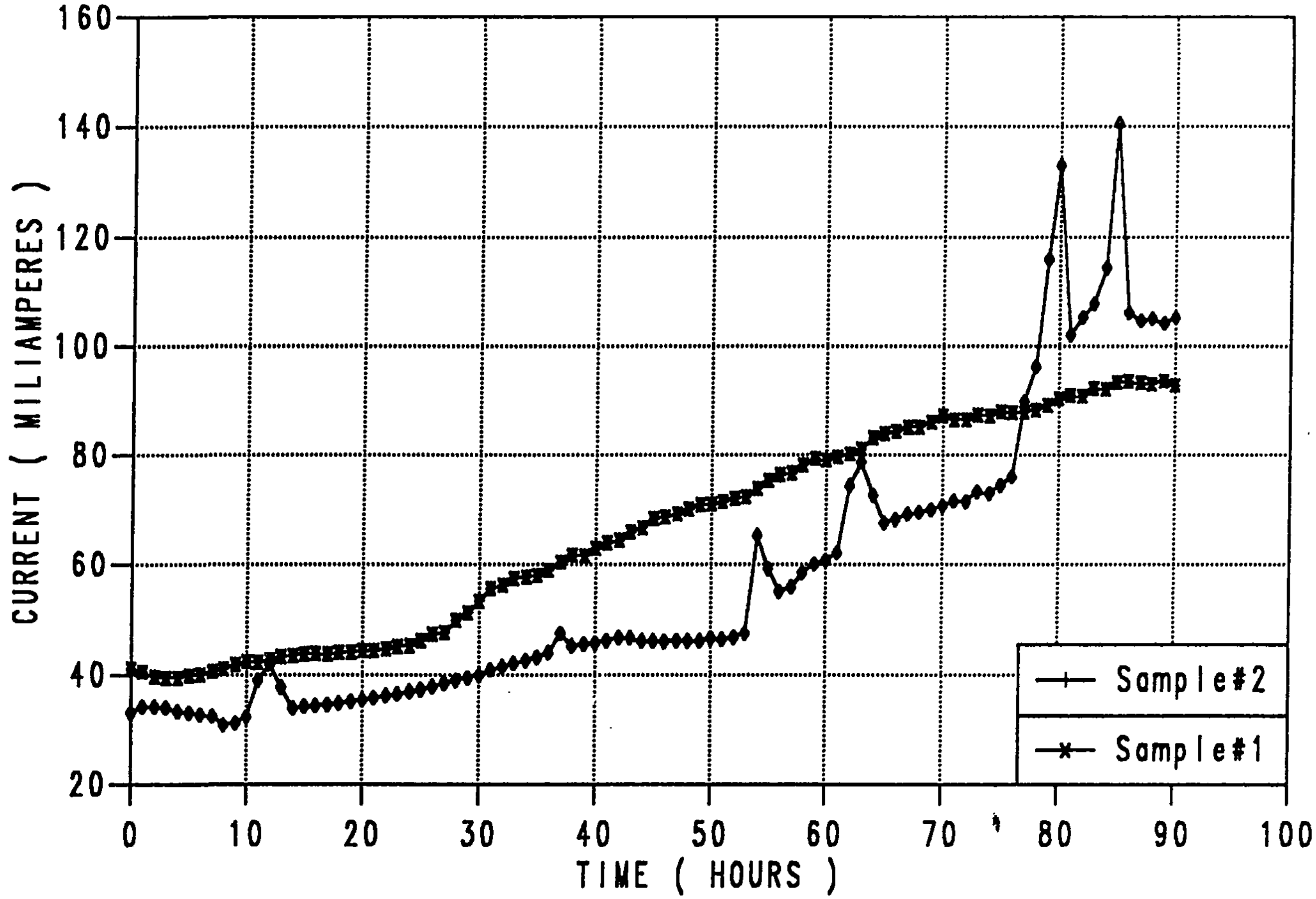


Fig. 4.42: Impressed Current-time Curves For Ordinary Mortar Samples

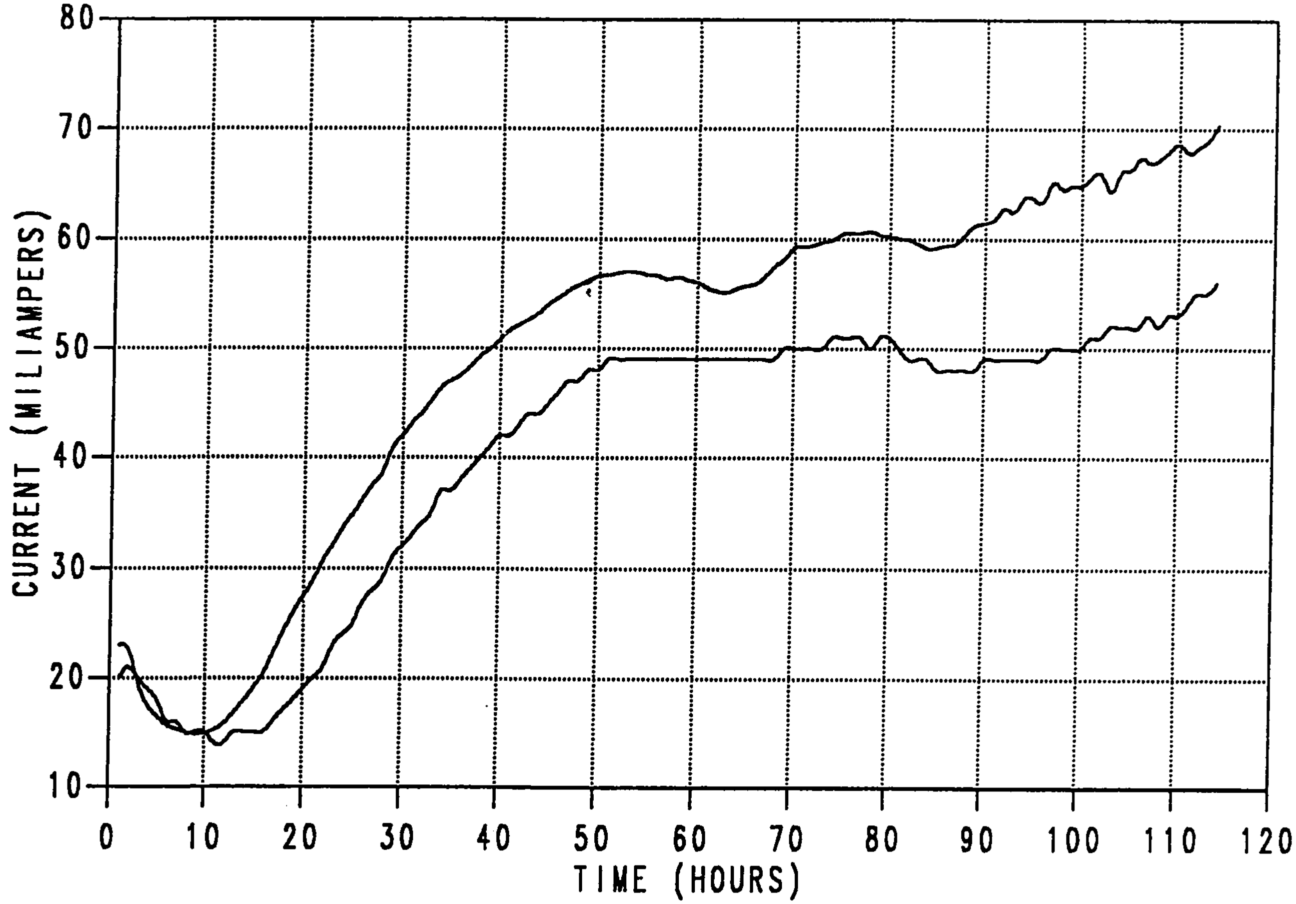


Fig. 4.43: Impressed Current-Time Curve For Ferrocement Samples

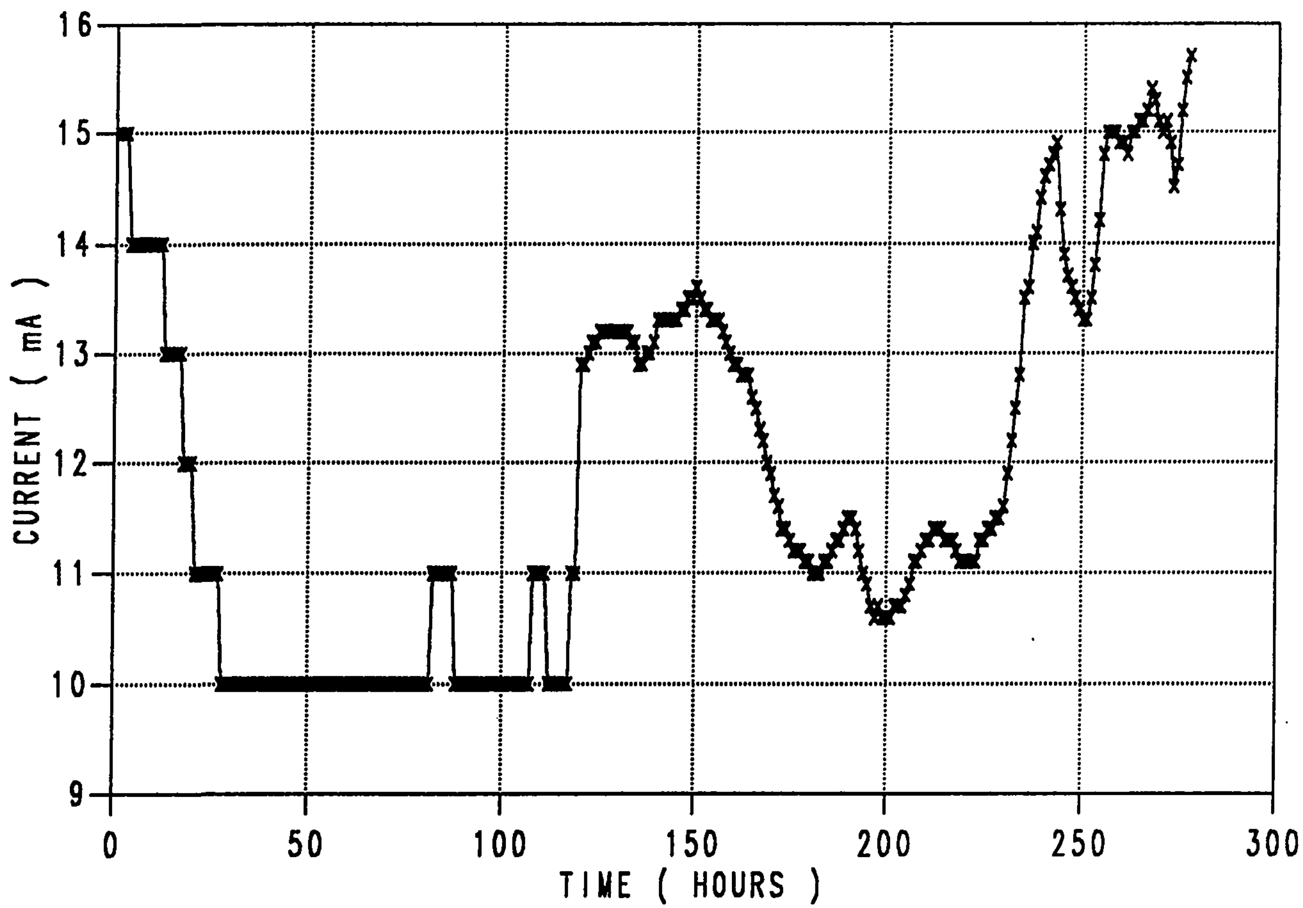


Fig. 4.44: Impressed Current-Time Curve For Polymer Mortar Samples

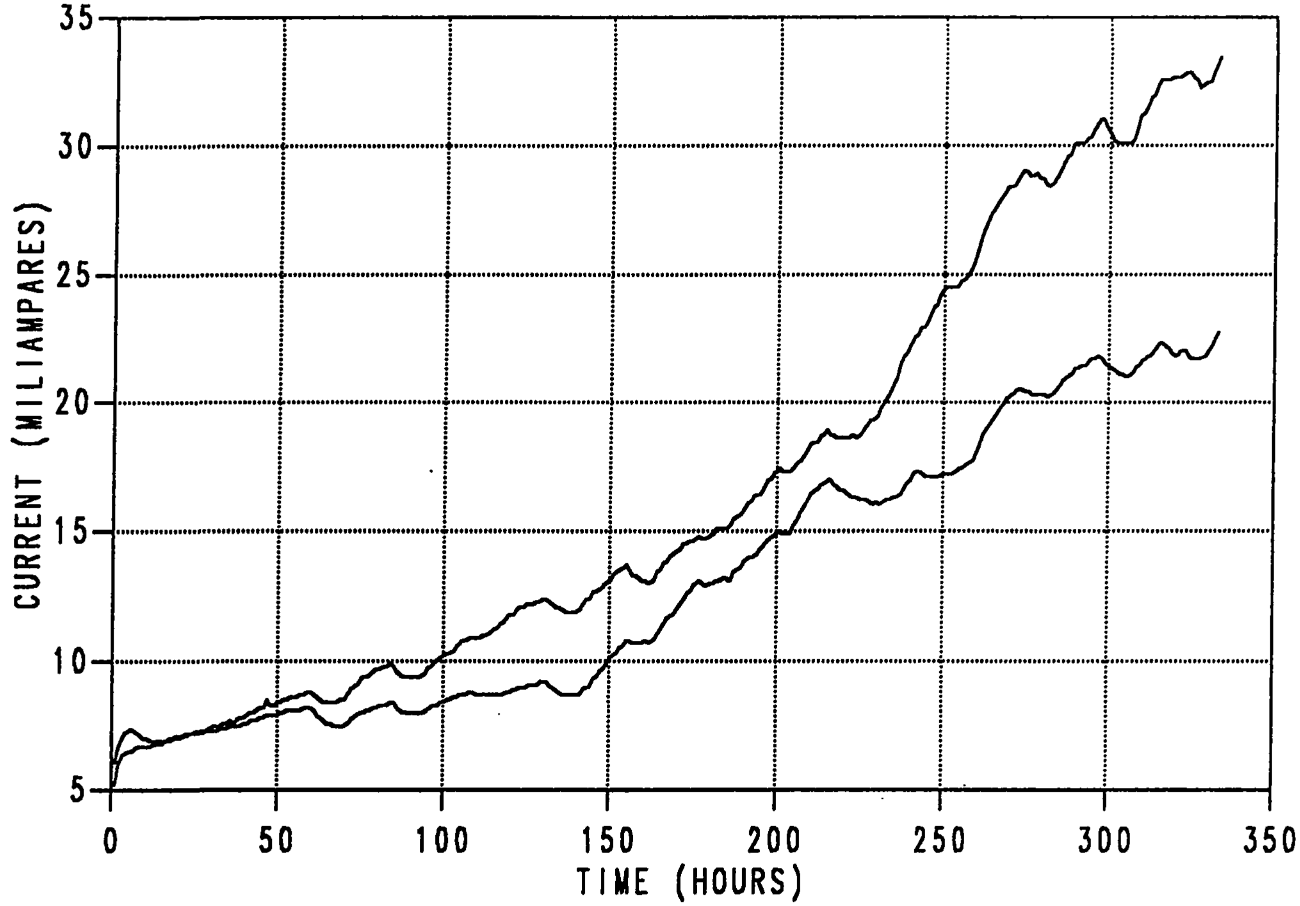


Fig. 4.45: Impressed Current-Time Curve For Slica fume Mortar Samples

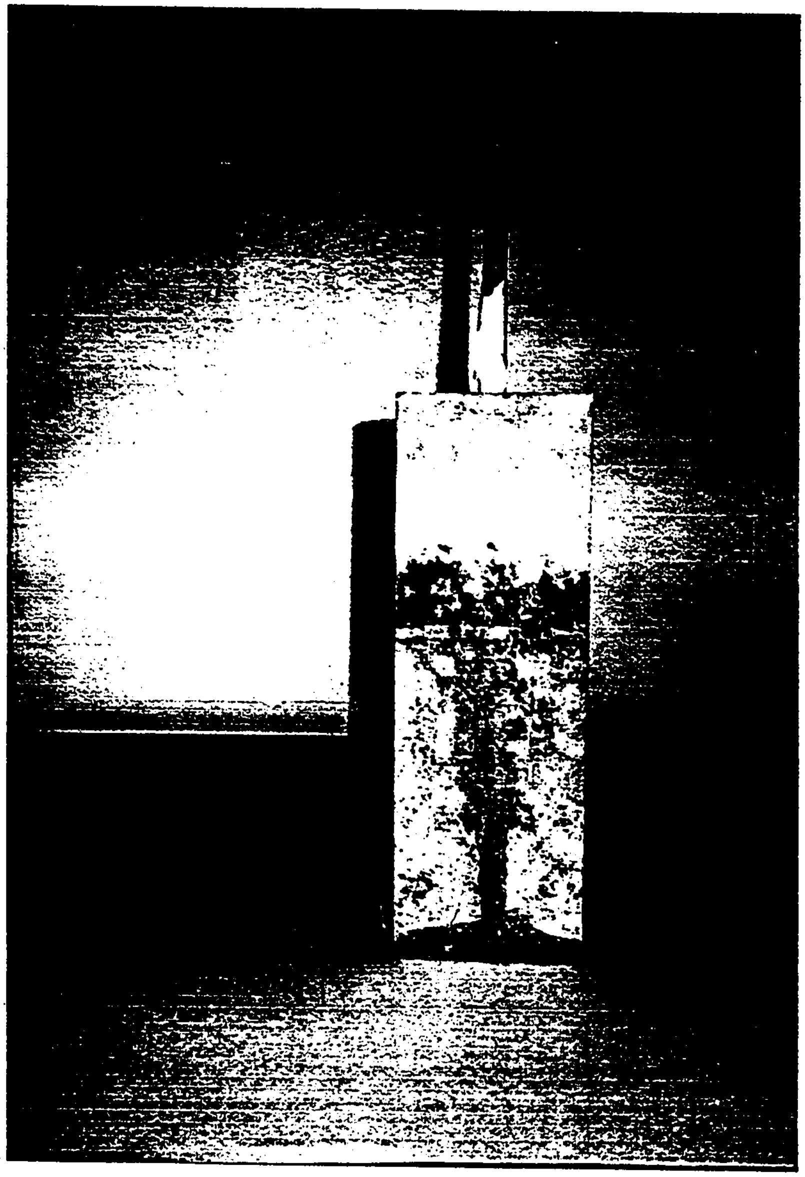


Plate 4.1 Plain Concrete Samples After Impressed Current Test.

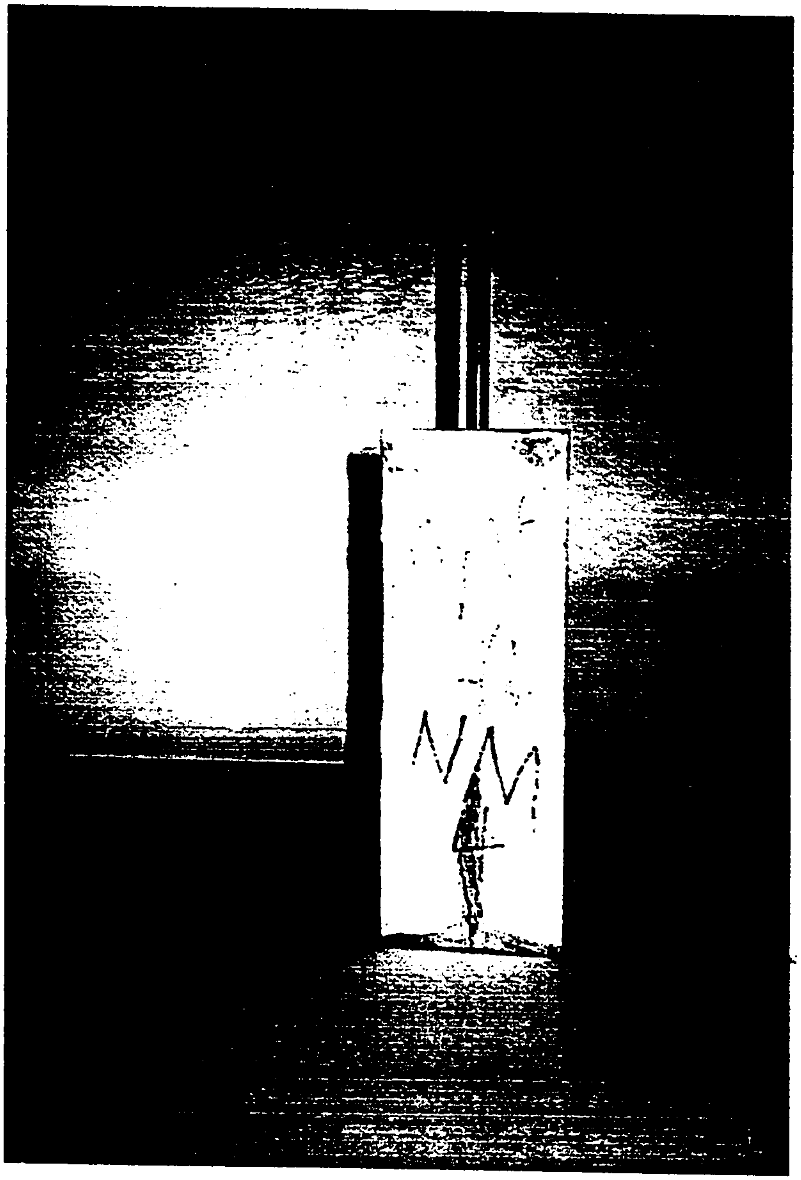


Plate 4.2 Normal Mortar Samples After Impressed Current Test.

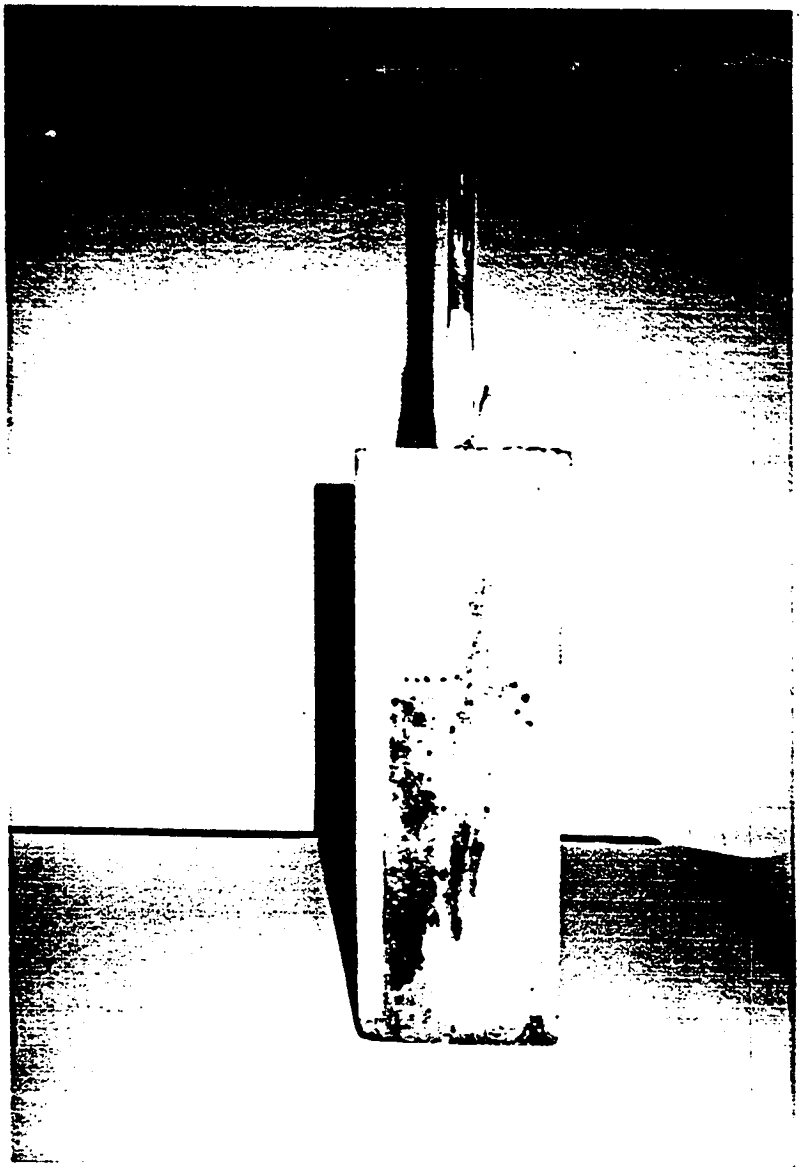


Plate 4.3 Ferrocement Samples After Impressed Current Test.

specimens lowers the electrical resistivity of the material, thus the current requirement is higher. In some specimens, which possess higher tensile strength, the build-up of the corrosion product does not lead to cracking of the specimens. Cracking can take place only when sufficient corrosion product has been formed. In such situations, it is too difficult to ascertain the time for cracking from the time-current curve. In such situations initial current density gives an indication of the resistivity of the material. The current requirements of denser materials are lower than those of the less denser materials. The initial current required for polarization of steel in repaired samples was in the range of 6 to 37 mA. The current requirement of specimens made with ordinary cement mortar and ferrocement is higher than in plain concrete. Samples made with polymer mortar and silica fume mortar required higher current for the polarization of steel compared to plain concrete. These results are summarized in Table 4.6.

Also shown in this table is the time taken for initiation of cracking in each sample. These data indicate a trend similar to the current data. Plain concrete samples took about 89 hours for initiation of cracking, whereas ordinary cement mortar samples took only 73 hours. The time for initiation of cracking was 116 and 150 hours respectively in polymer cement mortar and silica fume mortar specimens. Surface cracking was observed on these samples at a later period. The change in the slope of time-current curve was indicated after about 51 hours in ferrocement mortar samples. However, no surface cracking was observed. This is probably because of the presence of the galvanized steel mesh, which

Table 4.6: Impressed Current Test Data

Sample Type	Time (Hour)	Initial Current (mA)
Plain Concrete	89	16.8
Ordinary Cement Mortar	73	27
Ferrocement Mortar	51	37
Polymer Cement Mortar	116	14.7
Silica-Fume Mortar	150	6

increases the tensile strength of the ferrocement mortar.

4.4 Discussion of Results

4.4.1 Evaluation of Repair Materials

The performance of the repair materials was evaluated by conducting water permeability, chloride permeability and impressed current tests. These are some of the tests which are normally used by concrete technologists in evaluating the durability performance of repair materials. The results of these tests have been presented in the preceding Section 4.2 and 4.3. A summary of water permeability test results is presented in Table 4.7. In this table the repair materials are rated according to their performance. These data indicate that the performance of all the repair materials is better than the performance of plain concrete. The water and chloride permeability and corrosion resisting characteristics of samples prepared with silica fume and polymer modified cementitious mortar were better than the ordinary plain concrete samples. These results are in the line with those reported by other investigators [25, 85, 86]. Addition of silica fume to concrete as a partial replacement of cement causes pore refinement in such a system. Exact mechanisms by which the pore refinement occurs is not fully understood. However, Regourd et al. [87] observed that compared to the C-S-H phase in hydrated portland cements, a less compact C-S-H is found in well hydrated silica fume cement system. Evidently, if such a product forms as a result of chemical reaction between silica fume and lime, it would have the effect of filling up large empty spaces. This conversion of high density phase and large voids in a

Table 4.7: Performance Ratings of Repair Materials and Plain Concrete in Water Permeability Test.

PERFORMANCE RATING IN DECREASING ORDER
Polymer Modified Cementitious Mortar
Silica fume Mortar
Ferrocement Mortar
Ordinary Cement Mortar
Plain Concrete

portland cement paste system to low density products and small voids, as a result of pozzolanic reaction, appears to be the most logical explanation for increase in strength and decrease in permeability. Sellevold [88] using silica fume as an admixture has confirmed the process of pore refinement and its significance to strength and permeability.

In the polymer cementitious mortars, the polymer acts to reduce the water-cement ratio, thus improving several important properties of the mortar. More specifically, suitable polymers can produce simultaneous increase in strength, abrasion resistance and adhesion and decrease the water permeability, as well as shrinkage [30].

The water permeability of ferrocement mortar samples and the ordinary cement mortar samples was less than the water permeability of plain concrete. Use of galvanized wire mesh in the ferrocement mortar reduces shrinkage cracks which decreases the water permeability. The permeability of ordinary mortar is as expected lower than that of plain concrete. The increased water permeability in plain concrete compared to ordinary cement mortar may be due to weaker transition zone between the mortar and the aggregate and higher water absorption of the limestone aggregate compared to sand used in the mortar.

The performance of repair materials in the chloride permeability and impressed current tests is summarized in Table 4.8. These data indicate that the performance of specimens made with silica fume and polymer mortar was better than plain concrete specimens. The chloride permeability in the ordinary cement mortar specimens was, however,

Table 4.8: Performance Ratings of Repair Materials and Plain Concrete in Chloride Permeability and Impressed Current Testing.

PERFORMANCE RATING IN DECREASING ORDER	
Chloride Permeability	Impressed Current Testing
Silica fume Mortar	Silica fume Mortar
Polymer Cement Mortar	Polymer Cement Mortar
Plain Concrete	Plain Concrete
Ordinary Cement Mortar	Ordinary Cement Mortar
--------------------	Ferrocement Mortar

higher than in the plain concrete. The higher chloride permeability values in the ordinary mortar samples may be attributed to electrical resistivity of these samples. The electrical resistivity of ordinary mortar samples in saturated condition was 550 Ohms compared to about 1200 Ohms exhibited by plain concrete samples in saturated condition.

The performance of the repair materials in impressed current tests is similar to that shown in the chloride permeability test. In fact, in these two tests, the same principle is used. In the chloride permeability test, the total charge passed in 6-hour duration is calculated when a potential of 60 V is applied to the sample. In the impressed current testing the time to breakdown of passivity of reinforcing steel is used as a criterion to failure. Treadaway [81], has suggested a galvanostatic impressed current testing to evaluate the performance of repair mortars. In this technique an electronically controlled constant current is applied to a centrally-disposed mild steel electrode contained within a cylinder of the mortar under test which itself is immersed in a saturated solution of calcium hydroxide. The current is applied through an external counter electrode. The potential of the test electrode is monitored over a period of time and its change provides an indication of the ability of the test to initiate or inhibit corrosion. A rise in potential from the initial value indicates protection while a fall suggests loss of passivity and initiation of corrosion. The time taken for loss of passivity (or initiation of corrosion) by ferrocement and ordinary mortar samples is 51 and 73 hours respectively. Plain concrete samples took about 89 hours to fail. This was probably because of lower electrical resistivity exhibited by these samples compared to plain concrete.

The current required for polarizing rebars in ferrocement, ordinary mortar and plain concrete was 16.8, 27, and 37 mA respectively. Higher polarizing current requirement indicates lower resistivity. The higher current requirements of ferrocement samples may be attributed to the inclusion of galvanized steel mesh in the mortar samples. The results of impressed current testing indicate that where the structural components are exposed to water at all times, or electric current, or chloride ions, ferrocement and ordinary cement mortar should be used. Due to lower resistivity offered by these materials in saturated condition the chances of corrosion are increased. Samples made with silica fume and polymer modified cementitious mortar showed much better resistance to corrosion than plain concrete specimen. The time taken for initiation of cracking in silica fume mortar and polymer modified cementitious mortar samples was 150 and 116 hours respectively. In these specimens cracking was evident after more than two weeks. In structural components exposed to water silica fume and polymer modified cementitious mortar are recommended for repair.

4.4.2 Corrosion of Rebars in Beam Specimens

Reinforced concrete beams were repaired using ordinary cementitious mortar, ferrocement mortar and polymer modified cementitious mortar. The beams were partially immersed in the sodium chloride solution. The corrosion activity was monitored by measuring half-cell potentials and measuring corrosion rates using Tafel-Plot technique. The half-cell potentials after 120 days of exposure to the salt solution are shown in

Figure 4.10 and the corrosion rates of rebars in these beams are shown in Figure 4.29 and Table 4.2. The performance ratings of the repair materials in inhibiting rebar corrosion based on half-cell potential and corrosion rate measurements are shown in Table 4.9. These data indicate lower corrosion of rebars in repaired beams compared to plain concrete beams. Corrosion of rebars in beams repaired with polymer cementitious mortar seem to be higher than those of rebars in beams repaired with ferrocement and ordinary cement mortar. But the variation in half-cell potential and corrosion rate values in polymer modified cementitious mortar repaired beam and those repaired with ferrocement and ordinary mortar is not significant.

Slightly higher corrosion rates of rebars in the polymer modified mortar beams, compared to those in ferrocement and ordinary mortar repaired beams may be ascribed to the workability of the polymer modified cementitious mortar used. The water-mortar ratio used for the mix was 0.12. This produced a stiff mortar which could not penetrate to all the chipped parts of the beam during casting and vibration. Honeycombing were observed at the interface between new mortar and old concrete. This can be avoided by increasing the water-mortar ratio or after removing the moulds polymer mortar can be applied on the honeycombed surface. In fact, the manufacturer of this material was made aware of this problem. The manufacturer has since then changed the mix design, and has come up with a more workable repair material with water-mortar ratio of 0.19.

In general, corrosion of rebars in beams repaired by the repair

Table 4.9: Performance Ratings of Repaired and Plain Concrete Beams in Inhibiting Rebar Corrosion.

PERFORMANCE RATING IN DECREASING ORDER	
Half-Cell Potential	Corrosion Rate
Ordinary Cement Mortar	Ordinary Cement Mortar
Ferrocement Mortar	Ferrocement Mortar
Polymer Cement Mortar	Polymer Cement Mortar
Plain Concrete	Plain Concrete

materials investigated is lower than those in plain concrete. There is uncertainty about the performance ratings among these materials. It is too early to give any definite opinion about the performance of these materials at this time. More data will be needed to make a realistic analysis.

4.4.3 Effect of Thermal Cycling on Corrosion of Rebars in Beams

The half-cell potentials and corrosion rates of rebars in beams subjected to heat-cool cycling are presented in Figures 4.11 through 4.21. The performance ratings are shown in Table 4.10. Also the effect of heat-cool cycling in the repaired beams are shown in Figures 4.46 and 4.47, these two Figures show a comparison of half-cell potentials and corrosion rates for the repaired beams which were subjected to heat-cool cycling and those which were not subjected to heat-cool cycling. The half-cell potentials of rebars in beams subjected to thermal cycling are more than those in the beams which were not subjected to thermal cycling. The corrosion rate data indicated a similar behavior. The corrosion rates of rebars in beams subjected to heat-cool cycling were 1.2 to 1.6 times the corrosion rates of rebars in the beams which were not subjected to thermal cycling. This indicates that thermal cycling increases the corrosion activity.

4.4.4 Electrochemical Noise Measurement

The electrochemical noise measurements have been obtained on steel bars embedded in concrete beams repaired using various repair materials. These measurements were also carried out on beams which were subjected to heat-cool cycling. The potential readings were recorded using a data

Table 4.10: Performance Ratings of Repaired and Plain Concrete Beams Subjected to Heat-Cool Cycles in Inhibiting Rebar Corrosion.

PERFORMANCE RATING IN DECREASING ORDER	
Half-Cell Potential	Corrosion Rate
Ordinary Cement Mortar	Ordinary Cement Mortar
Ferrocement Mortar	Ferrocement Mortar
Polymer Cement Mortar	Polymer Cement Mortar
Plain Concrete	Plain Concrete

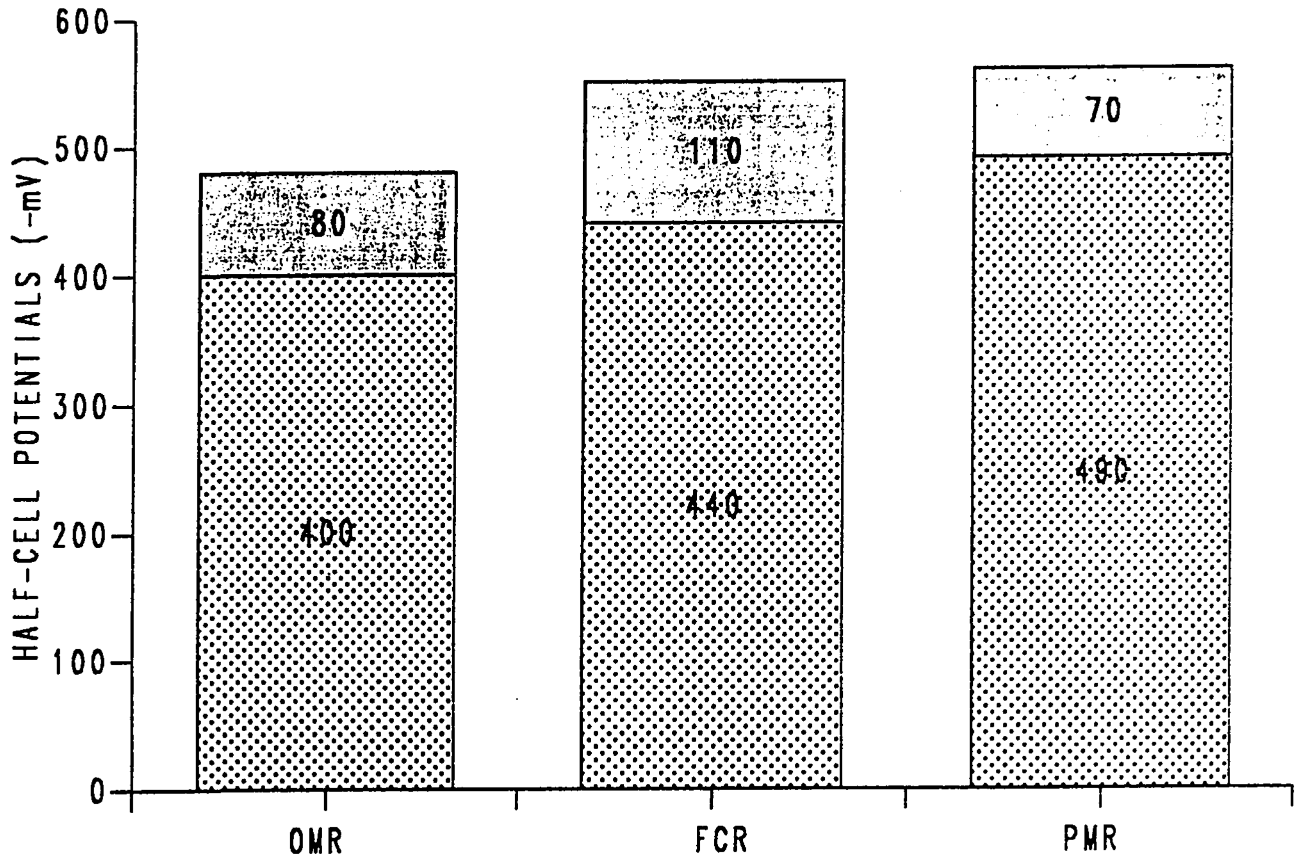


Fig. 4.46: Comparison of Half-Cell Potentials of Thermal and Non-Thermal Repaired Beams

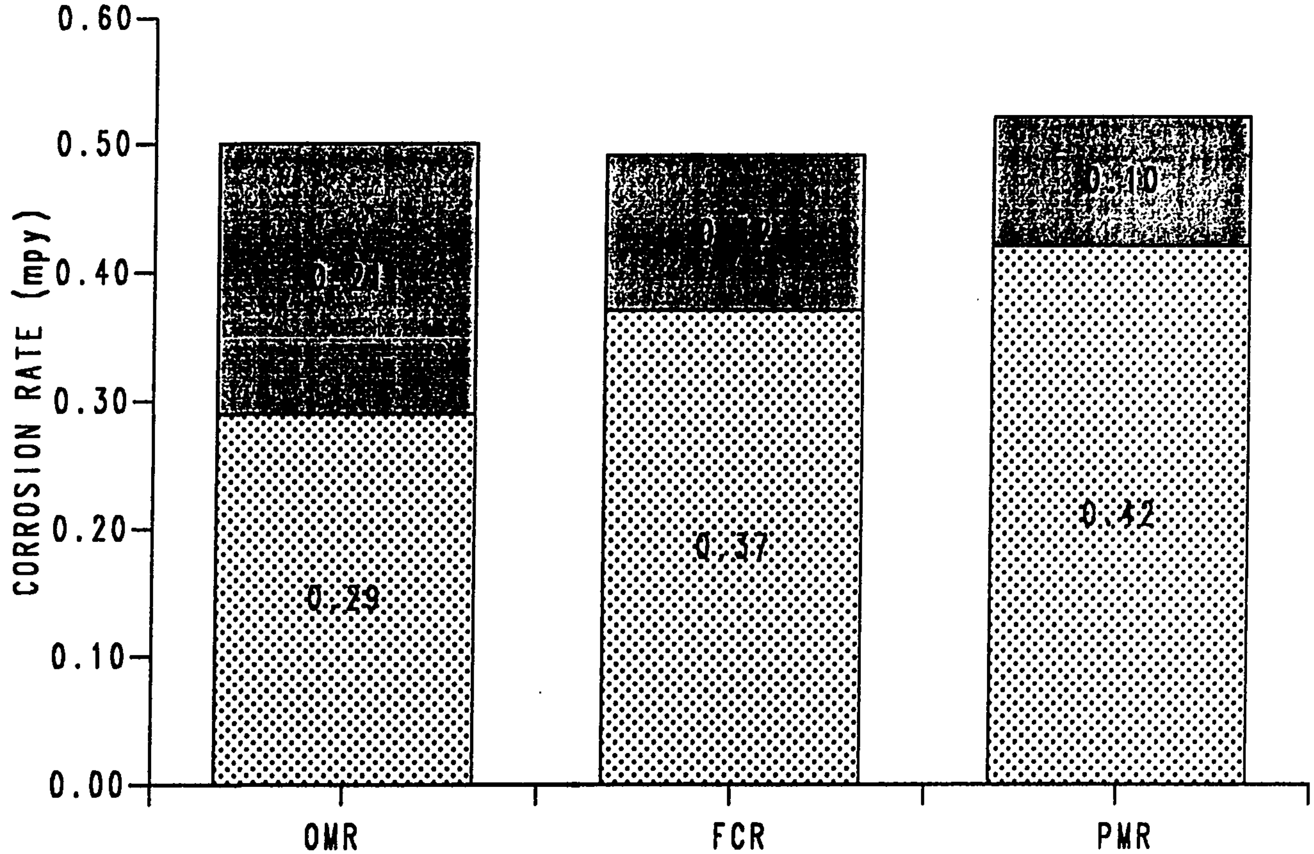


Fig. 4.47: Comparison of Corrosion Rate of Thermal and Non-Thermal Repaired Beams

logger at intervals of 15 seconds. The time potential noise data was recorded for a total duration of 900 seconds. These data are plotted in Figures 4.22 through 4.28. The potential noise data for normally cured plain concrete and repaired beams show a gradual fall in the potential-time curve. This drop in the half-cell potential value was very steep up to a time period of about 200 seconds, thereafter a gradual shift was observed in the remaining period of 700 seconds. The behavior of the time-potential record in concrete beams repaired with ordinary cementitious mortar and subjected to heat-cool cycling is similar to the one exhibited by normally cured specimens. The potential noise data for concrete beams repaired using ferrocement and polymer cementitious mortar contained a series of peaks and valleys which were characterized by potential drops up to 10 to 20 mv followed by a slow recovery. These data were analyzed to determine the standard deviation in the potential values. These standard deviation values are shown in Table 4.1

No relationship between the standard deviation values and the corrosion rate values could be established. Also, no data is presently available to compare the results of noise measurements carried out in this investigation. Dawson [89] and John and Eden [70] have determined potential noise variation in normal and salt contaminated concrete. The results obtained showed varying pattern of potential noise versus time record for these two concretes. Since this technique is more convenient for field studies there is a need to develop more data on the relation between noise measurements and corrosion rates of rebars in various concrete systems. The potential noise technique can be used as a complementary tool to the half-cell potential measurement and as such should greatly assist the materials scientists and concrete technologists in their development and research work to avoid more extensive destructive testing.

4.4.5 Evaluation of Repair Materials for Indoor Exposure

Specimens which were cured in normal conditions, i.e., which were not subjected to heat-cool treatment, can be treated as those which were exposed to indoor exposure. The results of various tests conducted on these samples is summarized in Table 4.11. The performance rating of these materials in various tests is shown in Table 4.12.

Water permeability, half-cell potential and corrosion rate data indicated that all the repair materials perform better than normal concrete beams. Chloride permeability and impressed current results indicated that the electrical resistivity of specimens made with ordinary cement mortar and ferrocement mortar is reduced considerably when they are saturated with water. This indicates that structural components continuously exposed to brackish water, or electric current, or chloride ions should not be repaired with ordinary cement mortar and ferrocement mortar. Structural components which are exposed to dry/semi-dry conditions can be repaired with these materials. Use of materials like silica fume mortar and polymer modified cementitious mortar should provide better protection to reinforcing steel. Appropriate repair material should be selected on the bases of cost and ease of application.

Table 4.11: Summary of the Results for Indoor Repair

Specimen Type	Water Permeability (mm)	Chloride Permeability (Coulomb)	Time for Cracking (Hours)	Half-Cell Potential (-mV)	Corrosion Rate (mpy)
Plain Concrete	30.0	1100	89	500	0.50
Normal Mortar	20.5	3015	73	400	0.29
Ferrocement	26.0	----	51	440	0.37
Polymer Mortar	14.3	1050	116	490	0.42
Silicafume	19.5	566	150	---	----

Table 4.12: Summary of Performance Rating for Indoor Repair

PERFORMANCE RATING IN DECREASING ORDER				
Water Permeability	Chloride Permeability	Impressed Current	Half-Cell Potential	Corrosion Rate
Polymer Mortar	Silica fume	Silica fume	Normal Mortar	Normal Mortar
Silica fume	Polymer Mortar	Polymer Mortar	Ferrocement	Ferrocement
Normal Mortar	Plain Concrete	Plain Concrete	Polymer Mortar	Polymer Mortar
Ferrocement	Normal Mortar	Normal Mortar	Plain Concrete	Plain Concrete
Plain Concrete	------------	Ferrocement	-------------	--------------

4.4.6 Evaluation of Repair Material for Outdoor Exposure

Specimens made with the repair materials, and the repaired beams were exposed to heat-cool cycling. This was done to evaluate the performance of these materials in outdoor exposure. The specimens were subjected to water permeability test. The half-cell potentials and corrosion rate of rebars in repaired beams were also evaluated. The results of these tests are summarized in Table 4.13. The performance ratings of these materials are provided in Table 4.14.

The depth of water penetration in all the repair materials was lower than that in plain concrete samples. The depth of water penetration was lower in silica fume and polymer mortar samples compared to ordinary mortar and ferrocement mortar. The performance of beams repaired with normal mortar was better than those repaired with ferrocement and polymer mortar in terms of half-cell potentials and corrosion rate of rebars. The difference in corrosion rates of rebars in all these specimens, however was very insignificant which indicate that the corrosion behavior of all repaired beams was approximately equal regardless of the repair material used. As such all these materials should be useful in improving the corrosion resistance of repaired beams. However, where structural components are exposed to brackish water, ordinary mortar and ferrocement should not be used for repair work.

4.4.7 Evaluation of Testing Techniques

In this investigation water permeability, chloride permeability,

Table 4.13: Summary of the Results for Outdoor Repair (60 Cycles)

Name of Material	Water Permeability (mm)	Half-Cell Potentials (-mV)	Corrson Rate (mpy)
Normal Mortar	56.3	480	0.50
Ferrocement	48.3	550	0.49
Polymer Mortar	37.0	560	0.52
Silica fume	45.0	---	----

Table 4.14: Summary of Performance Rating for Outdoor Repair

PERFORMANCE RATING IN DECREASING ORDER		
Water Permeability	Half-Cell Potential	Corrosion Rate
Polymer Mortar	Normal Mortar	Normal Mortar
Silica fume	Ferrocement	Ferrocement
Ferrocement	Polymer Mortar	Polymer Mortar
Normal Mortar	Plain Concrete	Plain Concrete
Plain Concrete	------------	----------

impressed current, half-cell potential monitoring and corrosion rate measurement techniques were used to evaluate the performance of repair materials. A brief discussion of the advantages and disadvantages of these techniques is provided in this section.

The water permeability technique can provide an indication of quantity of water that can flow through a material. However, initiation and sustenance of corrosion process is highly dependent on chloride diffusion and the flow of electrons in a material. The flow of electrons is dependent on the electrical resistivity of the material. As such water permeability results do not provide a useful information about the behavior of material in retarding initiation and growth of corrosion phenomenon.

Chloride permeability and impressed current techniques provide information on the diffusion of chloride ions in a material. The diffusion of chloride ions which are indirectly measured as the total charge passed in the chloride permeability test, and as the time to initiation of cracking in impressed current test. The flow of chloride ions is also dependent on the electrical resistivity of a material. Since the samples are exposed to chloride solutions in these tests, the possibility of decrease in the electrical resistivity when the structural components are exposed to brackish water is indicated in these tests.

The only disadvantage with these tests is that sample preparation with some materials like ferrocement is extremely difficult. Whenever sample preparation is easy and representative of field conditions, these two tests should be conducted for screening the repair materials.

Half-cell potential and corrosion rate evaluation techniques are useful as monitoring tools. These two techniques can be used as complementary to each other. Half-cell potentials can be useful in locating areas of localized corrosion. The corrosion rate measurement technique, either Tafel or linear polarization resistance can be used to assess the magnitude of the damage.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Based on the data developed in this investigation the following conclusions and recommendations can be made.

5.1 Conclusions

(1) The water permeability of all repair materials investigated was lower than the water permeability of plain concrete.

(2) The chloride permeability of silica fume and polymer modified cementitious mortar samples was lower than the chloride permeability of plain concrete. The chloride permeability of ordinary cementitious mortar was higher than that of plain concrete. This may be due to the lowering of the electrical resistivity of these materials in saturated condition. Lower electrical resistivity is conducive for the sustenance initiation and propagation of the

corrosion process.

(3) The trend of the impressed current data is similar to that shown by the chloride permeability test data.

(4) The time taken for initiation of corrosion in silica fume and polymer mortar specimens was much longer than the time taken by plain concrete specimens. The time taken for initiation of corrosion of rebars in ferrocement and ordinary mortar specimens was less than that in plain concrete specimens This is again attributed to the lower resistance offered by these specimens in saturated condition.

(5) The chloride permeability test and impressed current test data indicate that where structural components are exposed to brackish water and remain continuously wet, repair should not be carried out using ordinary mortar and/or ferrocement, preference should be given to silica fume and polymer modified cementitious mortars.

(6) The half-cell potentials of rebars in concrete beams repaired with ordinary cement mortar, ferrocement mortar and polymer modified cementitious mortar were lower than the half-cell potentials of rebars in original beams.

(7) The corrosion rate data indicated a similar trend, i.e. corrosion rates of rebars in the repaired beams were lower than those of rebars in original beams.

(8) The half-cell potentials of rebars in all the beams which were

subjected to heat-cool cycling were higher than the half half-cell potentials of rebars in the beams which were not subjected to heat-cool cycling.

(9) The corrosion rates of rebars in beams subjected to thermal cycling were about 1.2 to 1.6 times the corrosion rates of rebars in beams which were not subjected to thermal cycling.

(10) Repair of both indoor and outdoor components can be carried out using silica fume mortar, polymer mortar, ferrocement mortar and ordinary cement mortar. The choice of material should be based on economy and ease of application. However, where the structural components remain continuously wet, repair should be carried out using either silica fume mortar or polymer mortar.

(11) Among the evaluation techniques used in this investigation the chloride permeability and impressed current testing techniques provide a true evaluation of the repair material. As such these techniques should be used in the selection of appropriate repair material. Half-cell potential monitoring and corrosion rate measurements (Tafel or linear polarization resistance) techniques can be used as monitoring tools.

5.2. Recommendations

For further study the following points are suggested:

(1) The half cell potential monitoring and corrosion rate evaluation

studies on beam samples should be continued to evaluate the long-term performance of repair materials in inhibiting rebar corrosion.

(2) In this study the effect of heat-cool cycling on rebar corrosion was investigated under laboratory conditions, and the samples were subjected to dry heat. It is recommended that the corrosion of rebars in repaired beams subjected to various humidity-temperature regimes should be investigated.

(3) Also, exposure studies should be carried out to evaluate the performance of these materials in the natural conditions of the Arabian Gulf countries.

(4) Studies should be carried out to evaluate other cementitious materials like fly ash, slags and other corrosion inhibitors.

(5) Studies should be carried out to evaluate the resistance of these materials to sulphate ions.

(6) The effect of water-cement ratio and sand-cement ratio on on the performance of these repair materials should be evaluated.

(7) Study the bond and interface between the new repair materials and old concrete.

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